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A Review

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This research effort was initiated with the objective to complete a review and evaluation of the methodological and analytical techniques used to assess and quantify the economic impact of changes in agricultural crop yields.

The review focused on two major areas: (1) physical effects of man-made and natural factors on agricultural crop yield, and (2) methodologies and models used to evaluate and quantify the economic impacts of crop yield changes on the farm, the agricultural industry and finally the consumers.

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METHODOLOGIES FOR VALUATION OF AGRICULTURAL CROP YIELD CHANGES: A REVIEW

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FOREWORD

Effective regulatory and enforcement actions by the Environmental Protection Agency would be virtually impossible without sound scientific data on pollutants and their impact on environmental stability and human health. Responsibility for building this data base has been assigned to EPA's Office of Research and Development and its 15 major field installations, one of which is the Corvallis Environmental Research Laboratory (CERL).

The primary mission of the CERL is research on the effects of environmental pollutants on terrestrial, freshwater and marine ecosystem; the behavior, effects and control of pollutants in lake systems; and the development of predictive models on the movement of pollutant in the biosphere.

This project was initiated on November 1, 1976 and work was completed as of March 31, 1978.

A. F. Bartsch
Director, CERL

ABSTRACT

This research effort was initiated with the objective to complete a review and evaluation, within the constraints in time and resources of this project, of the methodological and analytical techniques used to assess and quantify the economic impact of changes in agricultural crop yields.

The review focused on two major areas: (1) physical effects of man-made and natural factors on agricultural crop yield, and (2) methodologies and models used to evaluate and quantify the economic impacts of crop yield changes on the farm, the agricultural industry and finally the consumers.

Investigation of the first area involved extensive literature review on the effects of the natural and man-made environmental factors, and their combinations on agricultural crop yields. The major natural environmental factors included in this report are climate and weather, soil and biological conditions. Air pollution is the main consideration under the man-made factors. Production functions in relation to individual or in combination with environmental factors are identified, when data are available. This area is presented in Section V of the report.

Methodologies and models for assessing economic impacts due to crop yield changes are considered in Sections VI, VII and VIII. Three alternative models are identified in Section VI for the evaluation of the cost to an individual farm due to changes in crop yield. These models are (a) mathematical optimization model, (b) simulation model, and (c) econometric model. Section VII outlines the regional input-output model and the regional spatial programming model as two feasible approaches in evaluating the secondary economic impacts. Finally, the market supply and demand theories are identified in Section VIII as relevant concepts in analyzing the overall impacts on consumers due to crop yield changes.

This report was submitted by the Eureka Laboratories, Inc. in the fulfillment of Grant No. R804957-010, under the sponsorship of the Environmental Protection Agency.

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ABBREVIATIONS

Abbreviations	Definition
ANOC	analysis of covariance
CES	constant elasticity of substitution
CS	consumer surpluses
ET	evapotranspiration
EV	expected value-variance
I-O	input-output
LAR	leaf area ratio
LP	linear programming
Ly	Langleys, (cal cm^{-2})
MLP	multiperiod linear programming
NAR	net assimilation rate
NSP	net social payoff
PET	potential evapotranspiration
PS	producers' surplus
QP	quadratic programming
RGR	relative growth rate
RP	recursive programming

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Ronald Oshima of the California Department of Food and Agriculture has spent many hours in reviewing Section V of this report on "Physical Effects of Man-Made and Natural Factors." His invaluable input to this report is gratefully acknowledged by the authors.

Special appreciation is extended to Ruby Reed for both her technical input to the agriculture crop yield section and her effort in manuscript preparation.

SECTION I

EXECUTIVE SUMMARY

This research effort is primarily concerned with the state-of-the-art review and evaluation of the methodologies and analytical techniques used in quantifying the economic impact of agricultural crop yield changes.

In achieving this objective, the review centered on two main areas. The first area is concerned with the physical effects of man-made and natural factors on agricultural crop yield, and the second on the methodologies and models for quantifying the economic impacts of crop yield changes on the farm, the agricultural industry and finally the consumers.

The entire report comprises eight sections, while the main body of the report is found in Section IV through VIII. A brief summary of the highlights of these five sections follows:

A. INTRODUCTION

The purpose of this project is to provide a literature review and evaluation of the methodologies and techniques available for the quantification of the economic impacts due to agricultural crop yield changes. The project was conducted in three phases: (1) information and data gathering; (2) review relevant information and data; and (3) information evaluation.

B. PHYSICAL EFFECTS OF MAN-MADE AND NATURAL FACTORS ON AGRICULTURAL CROP YIELD

The effects of physical factors, both natural and man-made, on crop yield were reviewed. These factors include light, temperature, water, wind, soil, biological factors and air pollution. Methods of estimating crop yield in relation to these environmental factors were also discussed.

The growth rate and dry matter production of whole plants is proportional to the light received or to the log of light intensity. Variations in crop yield have been observed to result from variations in the amount of light received. The growth rate of some crops is more sensitive to light deficiency at certain developmental stages than others.

The rate of growth increases approximately linearly with temperature between 5^{o} to $30^{o}C$ for temperate season crops. Growth stops at about $5^{o}C$, and the rate usually decreases rapidly after an optimum at 25^{o} to $35^{o}C$. Variations occur with plant species, age and influence of other environmental factors.

Plant growth and crop yield are controlled by the available water supply. The yield is approximately proportional to the amount of water used by the crop, although excessive water or periods of drought can cause temporary disruptions.

Plant growth is promoted by low velocity air movements. High velocity causes deleterious effects. The effects of wind have not been studied very extensively except in relation to windbreaks.

Soil influences plant growth by limiting the availability of nutrient ions because of the location of the ions in the soil complex, the relative amounts of the different ions adsorbed, the soil ion exchange capacity, the diffusional ion flux and the mass flow of ions in the soil matrix.

Crop losses from biological factors such as plant diseases, parasitic plants and insects, were estimated to equal about 10% of the crop. The estimates were based on surveys of various workers in the field.

Plant growth responses and visible leaf injury have been associated with different air pollutants. Ambient oxidants in some areas of the United States do clearly cause growth and yield reductions in some agricultural crops. Reported yields in nonfiltered field chambers were reduced compared with those in filtered chambers by up to 50% for citrus, potato, tobacco and soybean, up to 60% for grape and up to 29% for cotton.

Plant responses to air pollutant are subject to variations from environmental and genetic factors, distribution of exposure to pollutant and presence of pollutant mixtures. There is a distinct variation in susceptibility to air pollution among plant species, varieties and individuals.

Field survey and production function are the two methods widely used in estimating crop yield in relation to different environmental factors. The field survey has been used to estimate crop losses resulting from air pollution. Production functions are usually derived from multiple regression analysis which relates crop yield to different environmental variables such as weather or air pollution. Oshima (1976) has recently developed a method to produce crop loss-ozone dose functions under field conditions using ambient ozone variations at different sites in California.

There are difficulties with these methods for determining environmental variable-yield relationships. There are a number of factors influencing yield in the field which cannot be individually controlled. In various controlled facilities the reverse is true, where ambient conditions cannot be duplicated. For statistical analysis, the problems may include factor interactions, correlation between factors, limitations in the range of variables of regression analysis and uncertainties where quantitative measurements of factors is difficult.

C. METHODOLOGIES AND TECHNIQUES FOR QUANTIFYING ECONOMIC IMPACTS OF CROP YIELD CHANGES

In Sections VI - VIII an overview of methodologies is provided that may be pertinent to measuring the primary and secondary effects of physical factors in agriculture. The discussion in Section VI addressed the impact of crop yield changes on the farm level. Section VII is concerned with broader primary and secondary effects on the agricultural sector, intersectoral and interindustry effects, and regional effects of yield changes. Section VIII focuses specifically on how the externalities of yield changes in agriculture affect the consumer. A comprehensive assessment includes all of these aspects and their measurement may be thought of as an essential initial step in addressing the broader question of internalizing crop yield externalities through appropriate public policy. In addition to various quantitative techniques may be utilized to model the crop yield problem under consideration.

Section VI focuses on farm structure, profitability and risk changes due to crop yield changes induced by physical factors. We specifically concentrate on the following areas: (A) mathematical optimization modelled by representative farm and aggregated region, (B) simulation models, and (c) econometric models.

In VI, A, the linear programming (LP) model of the firm is a point of departure. Among the benefits of using LP are that it can solve complex, large optimization problems with relative speed. Additionally, the alternative impacts of varying parameters (such as air pollution levels, for example) can be readily derived.

On the other hand, LP is basically a comparative static, conditional normative tool. Multi-period models can adequately overcome the first problem, while recursive programming and risk inclusion help alleviate the second. The incorporation of risk is particularly important. It helps to reduce the discrepancy between the actual and predicted behavior of entrepreneurs. Thus, in aggregate studies it reduces the typical overestimation of supply that occurs due to the lack of specification of risk averse behavior. Risk inclusion also prevents unrealistic over-specialization in cropping activities.

Among alternative methods of including risk in a representative farm study, the direct derivation of E-V frontiers with quadratic programming is probably the most appropriate, assuming that a QP algorithm is available.

In VI, B, simulation models were considered to be an alternative approach to modelling the air pollution-agricultural sector system. Simulation is particularly flexible in the sense that it can manage large, complex stochastic systems, multiple objectives, interdisciplinary theoretical problems, and is by its very nature, dynamic. However, simulation models are non-optimizing and the conclusion was that in general, if data are available and an analytic optimizing model can be constructed, the latter is to be preferred.

Section VI, C gives a thorough treatment of econometric approaches. The econometric approach is positive, that is, focuses on existing relationships and not on what should be. Single equation "whole farm" production functions are a particularly good tool in diagnosing conditions of serious disequilibria. On the other hand, as the system under consideration becomes larger, with more producing units, perhaps the best use of "whole farm" functions are as inputs into aggregate regional linear or quadratic programming models.

Single equation functions are often subject to simultaneous equation bias which can be overcome by specifying one or more production relationships as equations in a structural system in which inputs, outputs, and other variables are simultaneously determined. A simultaneous system is not only logically superior to the single equation approach, but in the reduced form, allows for the derivation of dynamic impact multipliers, i.e., the effects of changes in exogenous variables sustained for a period of time on endogenous variables.

In Section VII the secondary impacts of physical factors damage on crop yields in a general equilibrium framework is considered. The methods discussed in VII are equally applicable to communities, regions, multiregional units, or nations. We extend the analysis beyond producers of agricultural commodities to consumers of such commodities - households and other industries in VII, A. In VII, B, consumer demand is incorporated in such a way that one can seek a social welfare optimum and measure the welfare effects of physical factors such as air pollution and pollution standards on producers and consumers.

Input-output analysis is a multi-market analytical technique that determines the interdependence of various sectors of the economy. It is a positive tool and differs from the approaches in Section VI in that the industry rather than the firm is the unit of production. It has been the most widely used tool in the study of regional and interregional independence.

The producing unit shifts to the region in VII, B. in which spatial programming models are reviewed. Among other things, such models are characterized by discrete producing and consuming regions. They also may incorporate many commodities related in supply and demand, multiple time periods, and storage activities. Spatial programming models, particularly the activity analysis version, have long been used in agricultural economics to derive efficient regional and interregional production, shipping patterns and resource allocation.

Of major interest to the externality problem under consideration is the nonlinear spatial programming model in which prices and quantities demanded are endogenous, that is, determined simultaneously within the model along with supply. In contrast, in the programming models discussed in VI, A demand is given. With normal negatively sloping demand functions and under the assumption of perfect competition, the appropriate maximand is net social payoff, or the sum producers' and consumers' surplus. In the absence of better measures, producers' and consumers' surplus measure the dollar values of producers' and consumers' welfare. These concepts may be used to identify gainers and losers due to alternative policy actions.

In recent years the net social payoff objective function has been modified to incorporate risk averse behavior. This is important to determining the effects of physical factors such as air pollution because they will alter the risk patterns of crops in different ways.

In Section VIII some basic concepts in demand theory are reviewed and the relevance of price and supply stability analysis to the measurement of the welfare effects of crop yield changes due to physical factors is indicated. Conceptually, we want to direct attention to the fact that when a given encironmental policy action such as that of air pollution is taken, the impact reverberates throughout the economic system.

SECTION II

CONCLUSIONS

The following conclusions are based on the literature review and evaluation conducted in this study.

(1) The growth rate and yield of plants are affected by physical factors such as light, temperature, water, wind, soil and biological factors. Quantitative data identifying the environmental variables and yield relationships are available in some areas while quite lacking in others.

(2) Considerable efforts have been extended to develop air pollution-crop yield functions in agricultural crops. While some good experimental data has been generated recently for several crops, much remains to be done in order to provide reliable data for meaningful economic impact assessment.

(3) Economic damage functions have been established in several studies. There are, however, inherent weaknesses in the data base of which the functions are derived, and other conceptual and empirical difficulties associated with the damage functions estimation. Therefore these functions should be used with proper understanding and caution.

(4) There are quite a number of econometric methodologies and techniques available for assessing economic impacts due to agricultural crop yield changes on the farm level, regional level, and the consumer level. These methodologies and techniques vary in complexities. In selecting from these techniques for one's use the choice will depend upon the project objectives and input data availability; criteria for these selection are covered in the text.

SECTION III

RECOMMENDATIONS

The quantitative relationship between agricultural crop yield and physical factors such as light, temperature, water, wind, soil and air pollution should continue to be investigated in order to provide more reliable functions. Priority should be given to the investigation of the effects of physical factor interactions on proudction. Major consideration should also be given to the consistency of techniques for evaluating changes in crop yield so that sound comparisons can be made between studies.

Under the assumption that reliable yield response functions can be estimated with either classical or Bayesian Techniques (the latter combines a priori knowledge with specific experimental results), appropriate methodologies are recommended with which the primary and secondary effects of crop yield changes can be measured. Primary effects are those at the individual farm level; secondary effects refer to impacts of yield changes on both the agricultural and non-agricultural sectors at the regional level and on the consumer.

In reality, one of the major problems in a California case study is expected to be the quantity and quality of data available for estimating yield response functions for the variety of crops found in typical California regions. Given this limitation, the recommended methodological approach at the farm level is to use yield response functions as inputs to an aggregate farm linear programming model (LP). With such a model, one can readily calculate changes in optimal cropping pattern (supply response), net returns, resource allocation and resource demand that result from changing the levels of given parameters. The level of air pollution is, of course, the parameter of major concern in this study. If we regard the estimation of yield response functions as the first phase in a regional study, the LP model may be regarded as the second phase in which one determines the primary economic effects of air pollution at the farm level.

Alternatively, if all data limitations were overcome in estimating yield response functions, such functions could be embedded in a simultaneous regional farm level production system. Dynamic multiplier analysis could then be used (with the system in its reduced form) to examine the impacts of changes in exogenous variables (such as air pollution) on the endogenous variables (for example, yields, output, profits) in the system.

An econometric model of a production system could also be used to simulate alternative outcomes under varying environmental regimes. While such a model is non-optimizing, it has advantages in that it can generate the time paths of changes in endogenous variables or monitor outcomes under alternative settings of decision variables.

In both the LP and econometric approaches, the risk and uncertainty inherent in farmers' can be incorporated into the models. The econometric approach is superior to the LP approach in that jointly determined structural relationships are estimated rather than predetermined. On the other hand, LP is an optimizing tool that can be made to be adequately predictive, and essentially is less demanding in terms of response function requirements.

Third phase of research involves the determination of the secondary regional effects of air pollution: on agricultural packers and processors, the transportation sector, employment, consumers, and other sectors interrelated with agriculture. Either the LP or econometric models of farm level impacts can used as inputs into such regional models.

Our recommended regional modelling approach is input-output (I-O) analysis. This is the most widely used methodology that accounts for the economic interdependence of sectors in a region. For given optimal farm level adjustments to alternative air pollution levels (for example, as ascertained in a farm level LP model), the I-O model may be used to determine existing and projected impacts in the entire regional economy. A dynamic extension of the static I-O model may be made in order to make long-run regional projections. The completely dynamic model is quite complex and requires the addition of a matrix of capital coefficients. Alternatively, judgemental assumptions about technological change can be used to make the model "partially" dynamic.

Another distinct attribute of I-O analysis is that the data collection process necessary to construct a regional transactions table is not as cumbersome as it once was. A substantial number of regional I-O studies have been completed in California. Consequently, there has been increased awareness of the need to maintain viable data bases as well as where to obtain regional data.

A regional spatial programming approach to measure the secondary effects of air pollution is a viable alternative to I-O analysis. In fact, it has several advantages: it is an optimizing technique; the objective function may be defined so as to maximize net social payoff; it can account for risk and uncertainty. These advantages are offset by a substantially greater and more difficult data collection effort relative to an I-O study.

With respect to consumer effects, the indirect impact of physical factors in agriculture will vary considerably according to the region selected for a case study. For instance, the effects of ozone on alfalfa yield in the South Coast Basin are likely to have only minor effects on milk prices faced by local consumers. On the other hand, physical factors damage to the lettuce crop in the Salinas Valley would have more significant price and quality effects - both on local consumers and on consumers in other areas of the country whom, at times, are completely dependent upon Salinas Valley lettuce. At the same time, since lettuce expenditures constitute such a small proportion of the family food budget, there will not be significant effects on overall consumer welfare.

SECTION IV

INTRODUCTION

The main objectives of any air pollution control programs are public health and safety protection and economic loss minimization. Agricultural crop yield reduction is a main concern in economic loss due to air pollution.

In assessing the economic impacts of air pollution on crop yield, reliable yield data and appropriate econometric methodologies are required. Agricultural crop yield data have mainly been generated by two methods, field surveys and laboratory experimentation.

Field survey is the most direct way of measuring crop yield in either a clean environment or in one impacted by physical factors such as air pollution, weather, pests or poor cultivation. There is one drawback in the field survey. The data accuracy depends very much on the experiences of the inspectors. They may or may not be able to separate the effects of different physical factors on crop yield.

There are difficulties involved with the laboratory approach also. Differing conditions and extraneous conditions not present in the laboratory, or poor laboratory work, can invalidate data developed with this method. Also, laboratory results at one concentration or condition are often linearly extrapolated to other concentrations or conditions. This induces error if dose-response is non-linear.

It becomes apparent, therefore, that in order to include reliable crop yield data for economic impact assessment, one has to examine and define those data in relation to specific conditions or physical factors under which the data are developed.

The crop yield data are usually transformed statistically into response functions. They are expressed in relation to different physical factors such as weather, soil conditions, and air pollution. The value of crop loss is then estimated by relating the functions to the total crop losses associated with different variables.

This is one of the most widely used approaches in the economic assessment of crop yield changes. This approach is direct and simplistic but not realistic. It does not account for any indirect economic effects such as labor forces, market behavior, etc. It considers only the economic impact to the farmer, and ignores the effects on the agriculture industry as a whole and the consumers.

This study was undertaken with those points discussed above in mind. It is the intention of this research effort to complete a review and evaluation of methodologies and techniques used for the quantification of economic impacts of agricultural crop yield changes brought about by the physical effects of natural and man-made factors. In achieving this objective, the project was conducted in three phases: (1) information and data gathering; (2) review relevant information and data; and (3) information evaluation. The main body of the report is presented in Sections V to VIII under four categories: (1) physical effects of man-made and natural factors on agricultural crop yield; (2) farm structure, profitability and risk changes due to agricultural crop yield changes; (3) secondary economic impacts due to agricultural crop yield changes; (4) overall impacts on consumers.

SECTION V

PHYSICAL EFFECTS OF MAN-MADE AND NATURAL FACTORS ON AGRICULTURAL CROP YIELD

A. ENVIRONMENT

Plant growth under natural ambient conditions is a complicated process in which the input of radiant energy is used to convert carbon dioxide and various elements from the soil into photosynthates. The growth process is influenced by plant genotype, environmental variables and cultural or other external parameters. The following section reviews research on the major environmental factors as they are related to plant growth or yield. Research carried out out under controlled laboratory conditions is considered first, and is followed by results from field studies.

"Yield", in agricultural production, is concerned with that part of a plant or crop which can be marketed as food or otherwise utilized for some economic gain. This marketable portion may involve almost any plant part which may be harvested at various stages of maturity. Studies of the relationship of environmental factors and to crop yield have been an area of enormous interest (Thompson, 1962; Haun, 1973; Kuchl *et al*, 1976), but most investigations are not directly related to economic concerns. Most experimental results were derived from studies investigated under controlled conditions or artificial environments and in many cases yield was measured over relatively short time intervals (Thorne, 1970). Over the short term yield may be measured as growth rate or more commonly as photosynthetic productivity (Setlik, 1970). Photosynthetic productivity is determined by measurement of carbon dioxide uptake or by periodic measurement of the dry weight increase of plant parts (Blcakman, 1961).

1. Climate and Weather

Climate represents the overall trend of weather in a region over a long period of time, and *weather* refers to the daily fluctuations of meteorological factors (Whyte, 1960; Evans, 1963). The types of crops which may be grown in a particular area and the maximum yield attainable are dependent on climate, but the yearly variation in yield for crops which are grown frequently is determined primarily by weather variables (Thompson, 1962; Warren Wilson, 1967; Haun, 1973).

a. Light

Radiation. The radiant flux density averages about 1390 W m^{-2} on the irradiated side of the earth's atmosphere. About 75 percent of this radiation may reach the earth's surface on a clear day, and about 25 percent on a cloudy day. About half of the radiation reaching the earth's surface is in the visible light, photosynthetically active (0.4-0.7 μm) wavelength band (Milthorpe and Moorby, 1974). The radiation flux densities vary with latitude and the time of year.

Photosynthetic processes. The primary influence of light (radiation) on plant growth and yield is through photosynthesis. Photosynthesis consists of at least three processes which are influenced by climatic factors (Gaastra, 1962):

(1) a diffusion process in which CO_2 (carbon dioxide) is transferred from the external air to the site of the reaction in chloroplasts. Influenced by temperature.

(2) a photochemical process by which light energy is converted into chemical energy and the reduction of CO_2 into carbohydrate. Influenced by light only.

(3) biochemical processes in which the energy produced by light is used for the reduction of CO_2. Biochemical processes are strongly influenced by temperature.

Light intensity and photosynthesis. Assuming ample water supply and nutritional level, photosynthetic rates may be limited by the CO_2 concentration, temperature or available light. Photosynthetic rates of most plants increase linearly with light intensity until maximal rates are achieved provided temperature and CO_2 concentration remains constant. Further increases in light intensity then fail to increase the photosynthetic rate. In laboratory studies Bohning and Burnside (1956) found light saturation intensities of about 2500 foot-candles for several field crops. Others (listed by Chang, 1968) have reported values of 3000 to 4000 and even up to 6000 foot-candles (full sunlight at noon usually exceeds 10,000 foot-candles) for sugar cane. Hesketh and Baker (1967) did not find a saturation intensity for corn at irradiances up to 1400 $W\ m^{-2}$, an intensity greater than full sunlight. Monteith (1965) has stated that laboratory measurement of photosynthesis in relation to light intensity, at fixed CO_2 concentration can be fitted to the curve:

$$P = (a + \frac{b}{I})^{-1} \qquad (1)$$

where P is the rate of photosynthesis (grams carbohydrate per square meter leaf area per hour), I is light intensity (Langleys/hour), and a and b are constants which vary for each plant variety.

This intensity response curve in terms of CO_2 uptake had been described by Hesketh (1963) as a rectangular hyperbola of the form:

$$Q = Q_{max}\ K\ I\ (1 + K\ I)^{-1} \qquad (2)$$

where Q = the CO_2 uptake in mg/dm^2 leaf area/hr, Q_{max} is the uptake at saturating light intensity, I is intensity and K is a constant for the plant. At $I > 0.25$ Langleys (Ly) per minute the response fits the curve for 9 species tested. The fit where $I < 0.25$ Ly was poor apparently because of interference from respiratory CO_2. Q_{max} could be determined more easily as the intercept with the equation in the linear form:

$$\frac{1}{Q} = \frac{1}{Q_{max}K\ I} + \frac{1}{Q_{max}}$$

Carbon dioxide and photosynthesis. At high light intensities photosynthetic rates can be elevated two or three times by increasing the CO_2 content to about 0.13 percent compared to the normal atmospheric content of 0.03 percent (Chapman and Loomis, 1953; Gaastra, 1959, 1962; Waggoner, Moss and Hesketh, 1963).

Within plant communities there are variations in the ambient CO_2 content, which depend on the consumption of CO_2 by the plants, and the input through diffusion or air movements (Lemon, 1960; Setlik, 1970). Tamm and Krysch (1961) found the minimum CO_2 concentrations within a crop canopy were between 0.025 and 0.029 percent, and a 0.02 percent minimum was reported by Chapman *et al* (1954). The local carbon dioxide deficit may, therefore, cause a decrease of 10 to 20 percent in the rate of photosynthesis (Chang, 1968).

Temperature and photosynthesis. The photosynthatic rates of plants increase with temperature until maximums are reached. The influence of temperature on photosynthesis varies greatly with plant species or variety. Molga (1962) showed there was linear increases in photosynthesis of potato, tomato, and cucumber plants between 10° and 30°C, the rate being about 5 times as great at the latter temperature. After optimal rates at 30°C there was a sharp drop with temperature above 37°C. Temperature optima near 25° or 30°C are reported to be typical of temperate and tropical plants (Milthorpe and Moorby, 1974), but for some arctic and alpine plants the optimum may be as low as 15°C (Mooney and Billings, 1961). In addition to differences among plant species, the temperature optimum may be influenced by the previous environment of the plants. For example, when measured at 30°C the photosynthesis of *Panicum coloratum* plants grown previously at 20°C could be doubled by subjecting them to 30°C overnight (Ludlow and Wilson, 1971).

Dry weight increase--Growth chambers. Growth or yield in terms of dry weight increase have been measured in relation to light intensity under controlled environment conditions. Such studies are valuable since the effects of other factors, e.g. temperature, which may be correlated with light under natural conditions (Warren Wilson, 1967) can be eliminated. Most of these investigations have used a limited range of light intensities, only 2 or 3 intensities in many cases (Hussey, 1965; Silsbury, 1971).

Hussey (1965) measured the dry weights of tomato plants grown at 400 and 800 foot-candles. The weights at the latter intensity were about twice as great as the lower. There was a temperature optimum near 23°C for both intensities. In barley plants, the log of dry weight was proportional to light intensity up to 60 cal cm^{-2} (Aspinall and Paleg, 1964).

Wheat plants were grown outside except for a period of 16 days either 5 or 21 days after the time of flowering. During the 16 days in growth rooms, they were exposed to light intensities of 374 or 740 J cm^{-2}, and those exposed to the higher intensity yielded about 15 percent more grain at maturity than those exposed to lower intensity.

The most extensive investigation of light intensity versus growth rate effects under controlled conditions was done by Rajan et al (1973). Five light intensities from 1.08 to 5.4 x 10^4 Lux were combined with six temperatures from 10 to 35°C. NAR (net assimilation rate), LAR (leaf area ratio), and RGR (relative growth rate) response surfaces were shown for cotton, sunflower, bean, and corn plants grown in each condition. The ranking of the maximal relative growth rates (g $g^{-1}day^{-1}$) were sunflower < corn < bean. The maximum RGR's were sunflower 0.29, corn 0.25, cotton 0.23, and bean 0.16. The RGR of bean was almost unaffected by light intensity but increased with temperature. RGRs for sunflower and corn increased to the highest point of temperature and light intensity used, but began to fall off at higher rates. Cotton showed a nearly linear increase with light intensity except at the lower temperatures.

Growth and dry weight increase--Field. Two methods have been used in studying the influence of light on growth and yield of plants in the field. In one, the light is reduced by shading to allow various proportions of full daylight to reach the plant (Blackman and Wilson, 1951; Blackman and Black, 1959a). In the second, more widely used method, an attempt is made to correlate observed variations in growth with the naturally occurring variations in light which result from cloudiness or seasonal change (Black, 1955; Eze, 1973; Warren Wilson, 1967).

Blackman and Black (1959a) found that when daylight was reduced by the use of screens the RGRs of sunflower, alfalfa, Lathyrus maritimum and three Trifolium species was linearly related to the log of the light intensity. Since in this relationship the RGR did not fall off at higher intensities, it was concluded that light was a limiting factor for growth of these species in southern England. In every one of 22 species tested under similar conditions, shading to one-half of full daylight caused a reduction in RGR (Blackman and Black, 1959b). In other tests even with some of the same species, e.g. sunflower, a curvilinear response was noted (Blackman, 1961). Deviations from a linear RGR-light intensity response result from differences in previous history of the plants (Blackman and Wilson, 1954). There is also a difference between isolated plants and those such as grasses which are grown in compact swards. The two species of grass tested by Blackman and Black (1959b) had RGR responses which were curvilinear with respect to the log of the light intensity.

In the foregoing investigations, plantings were made at various times during the growing season so that growth could be measured in plants of the same age. Multiple regression techniques have also been used in other experiments to analyze growth in plants started at frequent intervals.

Experiments of this type were carried out by Warren Wilson (1967) with rape, sunflower, and corn grown in an arid climate. The analysis accounted for 92 to 95 percent of the RGR variation in terms of mean temperature and radiation. The variation for rape was not influenced by changes in light level. Hodgson (1967) found 75 to 95 percent of the RGR variance of sunflower and *Vicia faba* growing in Scotland could be accounted for using the leaf area ratio in addition to the light and temperature variables. Eze (1973) determined correlations in terms of light, temperature and relative humidity for sunflower and bean in Sierra Leone of West Africa. Fifty-one to 52 percent of variance of RGR was accounted for. Voldeng *et al* (1973) included light, mean temperature and in some instances minimum temperature and accounted for 77 to 89 percent of RGR variation of corn growing in southern England. Equation for estimating RGR under the conditions used were included in each of these reports.

Warren Wilson (1967) has pointed out that difficulty may arise in multiple regression analyses of this kind when the variables are not independent. Light and temperature, for example, tend to be correlated, and Brenchley (1920) found r values of about 0.3 to 0.7 for those two variables. It was suggested that the influence of the correlated variables should be checked separately in controlled environment studies.

Comparisons of total global radiation for the growing season and yield have been made for a number of crops. Sibma (1970) determined correlations between the total radiation and yields of potatoes, sugar beets, peas, wheat, barley, flax and corn in a number of fields in the Netherlands. The correlations were found for annual yield data obtained over periods of 10 to 22 years for the different crops. An average of 57 percent of yield was accounted for in terms of the total global radiation in each growing season. The forage corn dry matter in an experiment in Britain (Phipps et al, 1975) was closely correlated with solar radiation, about 94 percent of variation being accounted for by the radiation changes.

There are some reports of yield reductions through shading where the economically important yield is produced at a late stage of development as with a grain crop. The degree of yield reduction by shading is dependent on the developmental stage in which shading occurs as well as the amount of light reduction (Evans and Wardlaw, 1976). Shading had least effect on wheat grain yield when it was given during the vegetative phase of growth (Fischer, 1975). In this stage, reducing the sunlight by 60 percent caused a yield reduction of less than 5 percent, while a similar reduction during the reproductive stage caused a yield reduction of up to 35 percent and in the grain filling period about 16 percent. Very similar effects of shading at different developmental stages of rice were reported by Yoshida and Parao (Evans and Wardlaw, 1976). Vegetative growth of wheat was reduced by shading whether or not there was an influence on grain yield (Fischer, 1975). Gifford *et al* (1973) found grain yield reduction of barley about equal with shading before or after anthesis. When the growing season for sugar beets was divided into 3 equal periods, shading in any one of them caused a reduction in root-size at final harvest (Watson *et al*, 1972). The dry matter of the root and the sugar content was proportional to the total radiation during the season regardless of the period in which it was received. Reduction of radiation by 56 percent reduced the dry matter of roots by about 50 percent.

b. Temperature

General characteristics. Plants have minimum, optimum, and maximum temperatures for growth, and these points have been called the cardinal temperatures. Cardinal temperatures are not precise values (Parker, 1946), but approximate values have been determined for most crop plants. With cool-season plants, the minimum is 0° to 5°C (Chang, 1968). It was established by Sachs (Went and Sheps, 1969) that cardinal temperatures do not remain constant during the life of the plant but are different for each developmental stage. This concept has been studied further and discussed by Went (1948, 1957) and others (Stanfield *et al*, 1966; Hartsema, 1961). Many plants have higher optimal temperatures in the early stages of growth as it has been found for peppers (Dorland and Went, 1947), peas (Went, 1957), beans (Viglierchio and Went, 1957), and tobacco (Camus and Went, 1952).

There is a variable relationship between temperature and growth which is dependent on the plant species. The general shape of the temperature-response curve shows a rapid increase in the lower range (0° to 15°C), a linear increase with temperature in the intermediate range (10° to 30° or 35°C) and a more rapid falling off at higher temperatures (Went, 1956, 1957; Erikson, 1959).

The reported rate of dry weight increase was about 80 percent greater at 30° than at 20°C in tomato (Abd El Rahman and Bierhuizen, 1959), soybean (Hofstra, 1972), and *Tidetromia* (Bjorkman *et al*, 1974). Each of these was over a linear portion of the response curve. In other instances, the Q_{10} for the 20° to 30° range was smaller (ca. 1.60) if the plants were older (Hofstra, 1972) or (ca. 1.27) if 30° was close to the optimum temperature (Bjorkman *et al*, 1974). This indicates that the experimentally determined temperature-growth-response curve may only apply to the plant used and to similar experimental conditions.

Other positive correlations between vegetative growth and temperature over a limited range have been recorded under controlled chamber conditions for pea (Dolan, 1972; Stanfield *et al*, 1966), tomato (Calvert, 1964; Went, 1948; Abd El Rahman and Bierhuizen, 1959), cotton, sunflower, bean, corn (Rajan *et al*, 1973), and other plants.

Some effects on final yield. There are relatively few growth chamber studies on the effect of temperature on the final yields of such crops as field grains and sugar beets. For studies within the usual range of outside temperatures, there may be little increase or a small yield decrease with higher temperatures although this varies with the crop tested.

When wheat plants were put into growth rooms at the flowering stage, the yield of grain was greater from plants maintained at 15°C than at

20°C (Thorne *et al*, 1968). Although the rate of dry weight increase of vegetative parts was higher at 20°C, the leaves died sooner. This reduced the leaf area available for photosynthesis and growth of the grain. In another experiment (Thorne *et al*, 1968), grain yield of wheat was higher in plants exposed during *spikelet* initiation to 15°C in the light period compared with those exposed to 20°C. In this instance, the higher yield was evidently due to the larger number of grains per ear formed at the lower temperature. A similar application of higher temperature for 16 days which started up to 3 weeks after anthesis also resulted in lower yield (Ford and Thorne, 1975). The final yield from sugar beets was increased by exposure to 6°C higher temperature during the period of greatest leaf expansion (Thorne *et al*, 1967).

Heat unit summations. Field studies of temperature effects on plant growth have been almost entirely confined to the determination of correlations based on the existing natural variations in temperature of the air and soil. The first of the many attempts to relate plant development to temperature in a quantitative way was done by Reaumur in the 18th century (Wang, 1960; Robertson, 1973). He proposed that a plant of a given variety required the same sum of daily mean temperature from planting to maturity regardless of the temperature variations. Reaumur's scheme has been modified in the development of the concept of a degree-day summation rather than a simple temperature summation. As presently used, a degree-day is the daily temperature in daylight hours above the minimum temperature needed for growth of the plant. It was later established that there was closer relationships with the developmental stage of the plant if the degree-day was multiplied by the average day length (Nuttonson, 1957). This can be expressed in the form of the equation:

$$\frac{M}{L}\sum_{p} (Tm - a) = K$$

where $$(Tm - a) = 0/Tm < a$$

(K) is the photothermal constant, (L) is the average day length during the growth period, (P) is the date of planting and (M) maturity, (Tm) is daily mean temperature, and (a) is the minimum temperature for growth of the plant.

A modification of the degree-day calculation was proposed by Gilmore and Rogers (1958) which takes into account temperatures above or below the optimum temperature range for growth of corn. Corrections were made for exposure to temperatures below 50° and above 86°F. The coefficient of variation of heat units required for corn development was reduced from 3.65 with only a 50° minimum to 1.63 with a 50° minimum and 86° maximum.

The degree-days and heat unit concepts have been criticized as oversimplifications because they do not consider the fact that (a) plants respond differently to temperature during different stages of their life cycles, (b) threshold temperatures may vary under different conditions, and (c) the effects of other environmental factors are omitted (Thornthwaite and Mather, 1954; Wang, 1960). It was considered accurate enough to be useful for some purposes.

The degree-days summation has been used with some success in the canning and packing industry for prediction of crop maturity (Robertson, 1973; Wang, 1960). Some of the crops which have been evaluated with regard to maturity are sweet corn, field corn, tomatoes, snap beans, lettuce, peas, wheat, flax and eggplant (Arnold, 1959). A polynomial regression curve, relating accumulated temperature to dry weight of corn over 150 days of growth, accounted for 92 percent of the observed variation (Phipps _et al_, 1975).

Field correlations. Continuing efforts have been put forth to develop methods and formulas for better estimating the developmental process of plant in terms of temperature. Ferguson (1958) suggested a method using hourly daytime temperatures and taking into account the non-linear relationship of the response. Robertson (1953) proposed a method for determining effective crop temperatures which included a factor for radiation balance. This method was expanded by Newman _et al_ (1967). Haun _et al_ (1972) used daily observations of developmental stages in estimation of the temperature response of snap beans.

Many of the techniques which are being developed do give improved estimates of growth in relation to temperature. They may be suited to providing scientific understanding to some degree but have little practical usefulness. In most of the recent field studies relating crop yields to temperature, other weather variables are also included in multiple regression analyses which try to determine which of the individual factors contribute significantly to yield variations (Huda _et al_, 1976; Waddington, 1973; Haun, 1973).

c. Water

Growing plants requires a continuous source of water which is taken up by the roots and evaporated from the aereal parts, primarily the leaves, during periods of high light intensity. Nevertheless, growth and reproduction can take place in plants exposed to varying degrees of water deficit. Most crop plants can also suffer deleterious effects from too much water.

Effects of water deficits. There are a large number of reports dealing with studies of the plant growth or yield response to water deficit. Because the plant and soil water status cannot be held constant, these studies, with few exceptions, do not show growth or yield in relation to a quantitative measurement of water status. Since nearly all of the dry weight increase occurring during plant growth represents CO_2 fixed by photosynthesis, photosynthesis has been used as a measure of growth during periods of soil and plant desiccation (Boyer and McPherson, 1975).

Photosynthesis continues at an undiminished rate with leaf water potentials of -4 to -8 bars. At lower water potentials, the shape of the response curves varied with the species tested. Sunflower (Boyer, 1970), tomato and loblolly pine (Brix, 1962) showed nearly linear decreases. The slopes for corn and soybeans continued to increase as the water potential approached -16 to -18 bars (Boyer, 1970). Plants exposed to these low water potentials do not necessarily show visible symptoms of desiccation although the photosynthetic rates are 15 percent or less of the rates in well-watered plants.

Some degree of adaptation to water stress is possible. For example, when water was withheld from corn plants throughout most of the grain-fill period, plants which had been grown previously in dry air became desiccated more slowly and produced a higher yield than plants previously in humid air (Boyer and McPherson, 1975).

The water potential and appearance of plants may return to normal in a very short time after they are re-watered following a period of drought. The rate of photosynthesis, however, may remain depressed for some time if the desiccation was sufficiently severe. Ashton (1956) reported 2 days were required for photosynthesis of sugar cane to return to near normal after drought. Similar effects were noted for apple trees (Schneider and Childers, 1941) and sunflower (Boyer, 1971).

The growth of leaves can be inhibited by only small degrees of desiccation compared with the amount which reduced photosynthesis (Hsiao, 1973; Boyer, 1970). For example, the enlargement of leaves was found to be greatest at -1.5 to -2.0 bars. Enlargement stopped at -4.0 bars in sunflower and at about -10 bars in corn (Boyer, 1971). Leaf water potentials, which attain low values during the day, usually rise again at night to the level of the soil water potential (Cowan, 1965). Leaf enlargement, therefore, may stop during the day in periods of low water supply but growth may resume at night.

There is some evidence that the response to water stress of plants in growth chambers may differ from that of plants growing in the field. In growth chamber studies, the leaf expansion rate decreased from -2 to -4 bars and ceased at -7 to -9 bars (Boyer, 1970; Turner and Begg, 1973; Watts, 1974). In field grown corn, however, Watts (1974) found moderate leaf extension rates at -9 bars, although in the growth chamber, leaf growth of corn stopped completely at -7 bars. Moreover, the data of Watts (1974) and McCree and Davis (1974) indicated that in the field leaf expansion rates continued at about the same rate day and night although leaf water potentials varied from -1 to -7 or -9 bars. The evidence indicates that caution must be used when extrapolating from controlled environment data to field conditions.

The transpiration - yield relationship. Another way of expressing the relationship between yield and water is to directly compare the amount of water transpired with the yield in dry matter. Transpiration is the loss of water from plants through the stomata of the leaves. A cause-and-effect relationship between transpiration and yield is thought to be unlikely (Milthorpe, 1961), but a close correlation between the two can be explained by the fact that both photosynthesis and transpiration rates are determined by light and by the soil moisture tension.

De Wit (1958) and Arkley (1963) have described studies in which yield and transpiration were measured in 10 crops, and in each case the relationship was linear. De Wit (1958) proposed the following relationship for areas of high radiation:

$$M = b\,W / E_o$$

where M is the total dry matter production, W is water transpired, E_o is free water evaporation, and b is a constant. For areas of low radiation, the formula was changed to:

$$M = c\,W$$

where c is a constant. The values of b and c are different for each crop and are subject to variation from climatic conditions, nutrient levels, and other variables.

The equations derived by De Wit were obtained from experiments with plants grown in containers.

Effects of water deficit on economic yield. Many field studies have shown that water deficits decrease crop yields and that irrigations increase yields (Fischer and Hagen, 1965; Salter and Goode, 1967). The degree of yield reduction with water deficit depends on the severity, timing and duration of the deficit, the plant species and variety, soil factors and weather factors. The impact on the economic yield also depends on what part of the crop is considered to be useful material to be harvested (Fischer and Hagen, 1965).

When the yield consists of leaf area development, as with crops such as pasture, ensilage, tabacco, and green vegetables, the effects of water stress are similar to those on total growth of the plant and are likely to be greater than effects on crops where yield consists of the dry matter stored in seeds. Hagen (1957), for example, found that moisture depletion of the soil which reduced green forage by 30 percent resulted in a 10 percent increase in yield of seeds. Also, Anderson and White (Begg and Turner, 1976) had a 47 percent reduction of total yield of green pea plant from lack of irrigation, but the yield of peas was reduced only 36 percent.

Effects of the timing of deficits. Many plants have certain stages in their development which are particularly sensitive to water deficiency (Salter and Goode, 1967) in terms of yield reduction. In the case of annual leafy crops such as lettuce, yield seems to be reduced if water deficits occur at any time during the development of a useable crop (Sale, 1966; Schwalen and Wharton, 1930; Salter and Goode, 1967). However, this was not found to be true in every investigation. Veihmeyer and Holland (1949) felt that irrigation near to harvest was not necessary for lettuce, and Schwalen and Wharton (1930) reported dry conditions early in the growing season greatly reduced head weight.

The yield of cereal grains is especially sensitive to water stress at 3 stages of crop development although some aspects of yield development are not common to all cereals (Slatyer, 1969). The first stage is that of floral initiation. The second is the stage of anthesis and fertilization, and the third is the stage of grain filling.

The number of floral primordia of wheat was reduced by 35 percent in barley plants when water was withheld for 42 days compared to those with continuous watering (Husain and Aspinall, 1970), and a similar effect was noted by Nicholls and May (1963) in water stressed barley. In wheat, the stage found to be most sensitive to water stress is approximately the last 15 days before anthesis. Fischer (1973) found a short period of plant water stress of -27 bars 10 days before ear emergence reduced grain yield of wheat almost to zero but has almost no effect on yield 12 days after ear emergence.

Sorghum is relatively insensitive to drought during floral initiation. Whiteman and Wilson (1965) subjected sorghum to "severe" stress for one week at various growth stages and found that inflorescence development could be suspended during the water stress period but could resume on rewatering.

Further examples of the influence of timing of water stress on grain yield are show in a study by Downey (1971). When water stress was allowed to develop for 20 days during male meiosis in corn, the total dry matter was reduced by 29 percent, but the grain yield was unaffected. When the drought was allowed to develop during grain filling, the reduction for total dry matter was 30 percent, but the reduction of grain yield was 47 percent.

Relating water supply to yield. There have been numerous procedures developed for the assessing the relationship between water supply and crop yield. Among these are correlations with measured rainfall, soil moisture, and evapotranspiration (Stanhill, 1973). Usually, the yield response correlations have not been related solely to water, but have been combined with other climatic variables such as temperature and radiation.

Total seasonal rainfalls have been correlated with yield with some success in arid zones, especially with the wheat crop. Cole (1938) related wheat yield to seasonal precipitation at 19 sites in the Great Plains area of the Unite States. The period covered was 1906-35 and precipitation accounted for 36 to 80 percent of the annual yield variation. There was considerable variation in the constants of the regression equations for different sites. These ranged from 8.40 kg $ha^{-1}mm^{-1}$ to 4.27, and intercepts ranged from -1450 to -530 kg ha^{-1}. Pengra (1952) related yields of cereal crops in South Dakota to rainfall which accounted for 37 percent of the yield. Staple and Lehane (1954a) found a similar correlation over 12 years for wheat production in Saskatchewan. The degree of correlation found in studies of this type was considered to be too low for practical applications (Stanhill, 1973).

Using a different approach, Walter (1963) determined that the dry matter yield of grasslands in south-west Africa was closely correlated with rainfall in regions of varying aridity.

Other climatic variables have been combined with rainfall in multiple curvilinear regression models. Thompson (1962) used this technique and divided rainfall into four periods during the year and combined this with mean air temperature in correlations with wheat production in 5 Great Plains states. A trend line for variations in technology was included. Correlation ranged from 0.86 to 0.96 in the equations.

When the rainfall in monthly periods was correlated with wheat yields in the Canadian prairie, the total annual production of the region could be predicted with an average deviation of 13 percent (Williams, 1969).

Soil moisture content. Plant growth is clearly dependent on the amount of water available in the soil, and there have been many investigations which try to quantitatively relate soil moisture status to growth. Especially in field investigations, there are difficulties associated with the determinations of the water status of the soil (Dale, 1968; Baier and Robertson, 1968; Stanhill, 1973). This is true because soils vary in their capacity to hold and to conduct water (Taylor, 1964).

Water available for plant growth is the root zone. A problem arises when the water potential and water content of soil in the root zone are measured. One must decide which depth is best, or measure water content or potential at several depths (Gardner, 1961). Detailed laboratory measurements may be necessary to properly characterize the moisture status of a soil for a particular crop (Visser, 1961; Sedgley et al, 1973). Baier and Robertson (1968) have concluded that "long-term records of soil moisture suitable for quantitative statistical investigations into crop-soil moisture relationships are not readily available." Various other methods have been developed to try to relate water use to crop yield (Baier, 1973; Stanhill, 1973). Some of them are discussed under "Evapotranspiration." A relationship between the measured water potential and crop yield has been reported for some crops.

A method called a "versatile soil moisture budget" developed in Canada by Baier and Robertson (1966) used calculated water available in 6 soil moisture zones of the soil profile. The estimate of water in these zones was based on standard weather observations and required calculation of daily estimates of potential evapotranspiration. It also required some knowledge of the moisture characteristics of the soil. The use of this model gave better estimates of wheat yields in 39 plantings during 5 seasons in Canada than did direct use of correlations with climatic variables (Baier and Robertson, 1968).

The yield of a number of crops (peas, potatoes, sugar beets, alfalfa) was found by Taylor (1952) to be linearly related to the soil water potential though there was considerable variation in the data. Bierhuizen (1961) showed that percentage fresh weight increases of lettuce, spinach, and radish were very similarly related to soil water potential.

Evapotranspiration. Evaporation from the soil surface and transpiration from leaves of the crop are the two sources of soil water losses which occur after drainage. However, it is difficult to separate these two processes in the field measurement. Therefore, the term evapotranspiration (ET) has been used in studying soil water status to represent the total water losses by evaporation and transpiration. The maximum ET, measured when water supply is non-limiting, is called potential ET (PET) (Penman, 1948). Since ET is a function of soil water contents, wind speed, humidity, air temperature and day length, there have been numerous attempts to relate crop production to ET, with the hope that the process of future crop yield estimation may be simplified by using ET measurement rather than by various climatic factors independently.

The relationship between ET and yield in the field may or may not be linear. Allison et al, (1958) showed a linear relationship between ET and yield of a number of crops grown in a lysimeter. Staple and Lehane (1954b) found that the yield was a linear function of ET with spring wheat grown in the tanks, and a curvilinear function to ET with wheat in the field plots. The effect on crop yield of changes in ET due to water moisture contents in the soil varies with various stages of plant growth, as illustrated by Chang et al (1963) in the study of sugar cane yield in Hawaii. Most crops have critical periods, during which a decrease of ET reduces economic yield much more than at other periods. Chang (1968, Table 19) lists moisture sensitive stages for 21 crops.

Methods for estimating PET can be classified into 5 categories: (1) direct measurement, (2) empirical methods, (3) energy balance calculation, (4) aerodynamic approach, and (5) use of evaporimeters. A brief discussion of the usefulness of these methods will be presented.

(1) Direct measurement. Lysimeters are soil tanks designed for growing crops under field condition, in which water loss can be directly measured by periodical weighing of the apparatus (Arnon, 1972). Meeting specific requirements (Chang, 1968), lysimeters are the most dependable means for direct PET measurement. A specially designed circular tent was introduced by Decker et al (1962) to measure ET from undisturbed plots of natural vegetation through determination of quantities of water vapor produced.

(2) Empirical methods. Many empirical formulas relating ET to meteorological measurements have been developed. The principle assumption for this method is that there is a direct correlation between crop water

requirements and the meteorological factors. Also, in attempting to establish a relatively simple formulation for practical use, a minimum number of factors are used.

The most popular and well-known formulas are: (a) Thornthwaite formula (Thornthwaite, 1948) expressing PET as an exponential function of mean monthly air temperature and day length; (b) Blaney-Criddle formula (Blaney and Criddle, 1962), the most widely used procedure for semiarid lands of western U.S., in which a crop factor showing seasonal variation is added to the ET estimation formulation, in addition to air temperature and day length factors; and (c) Makkink formula (Makkink, 1957), based on solar radiation measurements weighted according to air temperature, that is, a greater proportion of the solar radiation is used for ET at higher air temperature.

The reliability of the empirical methods for PET estimation is greatly improved when the formulas are calibrated for each specific crop in a given region (Tanner, 1967).

(3) Energy balance calculation. The energy balance method of calculating PET is based on the assumption that transpiration and evaporation are both controlled by the same physical factors, and therefore, ET is considered essentially a physical phenomenon which requires energy supply (Penman, 1948). A complete energy balance equation may be given as follows:

$$Q_n + H = S + A + ET + C + PS$$

where Q_n = net radiation; H = horizontal divergence of sensible and latent heat; S = heat flux to the soil; A = heat flux to the air; ET = evapotranspiration; C = heat storage in the crop; PS = photosynthesis. This equation was further simplified to:

$$Q_n = A + ET$$

by omitting factors S, C, PS because they are minor and negligible, and by dropping the H for there is no simple way to evaluate this factor.

Penman (1948), based on physical principles, derived a formula combining the energy balance approach and aerodynamic approach. This basic equation and its further modifications have been tested in various regions with various crops; such as: alfalfa-brome at Hancock, Wisconsin (Tanner and Pelton, 1960), perennial ryegrass at Davis, California (Pruitt, 1963), alfalfa at Gilat, Isreal (Stanhill, 1961). The testings clearly indicated the widest applicability of this method.

(4) Aerodynamic approach. This approach utilizes various aerodynamic methods to estimate the rate of water vapor diffusion related to ET (Thornthwaite and Holzman, 1939). A portable machine analyzer called "evapotron" was developed (Dyer, 1961) by CSIRO Division of Meteorological Physics. This approach is found less satisfying by various workers, in-

cluding a study conducted in Davis, California (Pruitt, 1963).

(5) Use of evaporimeters. Two types of evaporimeters are being used: (a) open water evaporation pans, and (b) porous surface type atmometers. The use of a evaporimeter to estimate ET is based on the similarity between evaporation and ET. The advantages of using evaporimeters are that they incorporate the effects of all meteorological factors, therefore, giving better estimates of short-term ET changes. Also, they can be used to estimate the ET throughout the life cycle of a crop (since ET rates vary with the age of a crop) (Chang, 1968). The most commonly used evaporation pan throughout the U.S. is the U.S. Weather Bureau Class A pan.

In evaluating the practical usefulness of each method mentioned above, one has to take into account, not only the accuracy of these methods, but also the convenience in field operation and the cost. Stanhill (1961) made a comparison of eight methods in Isreal, using a lysimeter as a standard. The simplest and least expensive method for obtaining a reasonable accuracy was the evaporating pans.

d. Wind

Plant growth is influenced by wind (Chang, 1968, Yoshino, 1974) in at least three ways. It may increase transpiration, change CO_2 intake and cause mechanical breakage of leaves and branches.

Water loss through transpiration increases up to a certain windspeed and then levels off (Stafelt, 1932) or decreases slightly (Hesse, 1954; Fibras, 1931).

The uptake of CO_2 and photosynthesis may be promoted somewhat by increasing windspeed (Lemon, 1963). Deneke (1931) found an increase in photosynthetic rates with windspeed to 167 cm/sec (3.7 mph) but there was no further increase with speed.

High velocity winds tend to be harmful to growth and yield (Wilson and Wadsworth, 1958; Pelton, 1967), but there are variations in response. Whitehead (1957) gave examples of (1) exposure evaders (flat or low stature), (2) exposure resistant (barley for example), and (3) exposure sensitive. Growth, as dry weight increase, in the first two categories was almost unaffected by high wind speed. In the sensitive plants, growth was inversely proportional to wind speed and approached zero at 60 m/sec. Wadsworth (1959) found growth of young rape (Brassica napus) plants was optimal at winds of 0.3 m/sec. and decreased at higher speeds. Changes in relative growth rate were small.

2. Soil Factors

The soil is the source of the mineral nutrients required by plants. The mineral ions occur in the soil in a variety of forms. Some are free in the soil solution; some are more or less tightly bound to the soil particles, and others are incorporated into the crystalline structure of some soil minerals.

It was originally suggested by Liebig (Russel, 1950) that the nutrient ions adsorbed by the colloidal fraction of the soil sere in some way utilized by plants, and the measured contents of ions in the soil complex is considered an index of the availability of these nutrients to crops (Millar, 1955). Nevertheless, there frequently is only a poor correlation between the growth of plants and the total content of a particular ion in the soil. This is because all of the ions in the soil are not readily available to plants. The degree to which ions are available depends to a great extent on the soil type. Some of the factors in the soil which affect availability are the ease of an ion's being replaced by other ions, the location of ions in the soil complex, the relative amounts of the different ions adsorbed, the ion exchange capacity, the diffusional ion flux for root absorption and the mass flow of ions through the soil matrix (Milthorp and Moorby, 1974).

The ion exchange capacity of a soil is a characteristic of particular significance in relation to the influence of soil type on nutrient availability. Except for saline and highly weathered soils, over 99 percent of the cations are absorbed and less than 1 percent are in soil solution (Thompson and Troeh, 1973). This ion exchange capacity of a soil also represents ion storage capacity which is a significant factor determining the response of crops to applied fertilizer. In addition, soils with a high exchange capacity are, in general, fertile and have a long lasting quality for crop production (Millar _et al_, 1966).

Phosphate has probably been studied more than other ions in relation to soil exchange capacities and availability to plants. An example of some differences which may be found is shown by an experiment of Biddiscombe _et al_ (1969) in which they applied phosphorous to three Austrailian soils of different exchange capacities. The amount of phosphorus remaining in solution after equilibrium ranged from 0.008 to 2.4 percent of the amount added. However, the soil with the smaller percent phosphorus in solution had at least a 100 times greater exchange capacity for phosphorus.

The amount of phosphorus absorbed by barley plants in a medium heavy loam was found to be directly related to the amount of exchangeable phosphorus in the soil (Russel et al, 1961). A similar linear relationship between applied phosphate and uptake was found for eight plant species by Keay _et al_ (1970). In another instance, the uptake of phosphate by kales varied, depending on the soil type they were grown in (Russell and Newbould, 1969).

Other characteristics of soil such as particle size, porosity, soil structure, pH, and organic matter content have importance in determining yield and suitability for the type of crop which may be grown in an area (Arnon, 1972; Thompson and Troeh, 1973).

Soil surveys have been made in many areas of the United States and other parts of the world (U.S. Department of Agriculture, 1957; Dewan and Famouri, 1964). The data from soil surveys can be used to estimate the yield potential of a soil (Steele, 1967). If an estimate of the influence of soil types on the variation in yield of one crop is desired over a wider area, such as a county, it would be necessary to determine the soil type under each planting. In addition, one must realize that the actual yield will also be determined by the combination of interactions among several different factors of soil, water, and crop management (Raeside, 1962).

3. Biological Factors

Disease and pest injury caused by viruses, bacteria, fungi, nematodes, parasitic seed plants and insects have long been recognized as important factors responsible for crop losses (Webster, 1972, Stapley and Gayner, 1969). The entire area of plant pathology is devoted to the study of plant diseases. Therefore, it is not the intent of this review to cover details in this area. A brief description of symptoms observed in the host plants, the extent of crop yield reduction caused by plant pests and diseases, and principles of pest and disease control will be presented here.

Diseased plants usually undergo various stages of morphological and physiological changes following the entrance of the disease-causing agents (Kenaga, 1970). The morphological changes that can easily be observed are: (1) abnormal host coloration, e.g., chlorosis, mottling, lesions; (2) wilting; (3) abnormal growth, e.g., overgrowth, dwarfing, replacement of host tissues by the parasites; (4) abscission of forliage and fruits; and (5) death, e.g., pre- and post-emergence damping off, rots.

There are two most commonly used expressions for estimating crop losses. One is expressed as percentage of potential crop yield, the other is in terms of monetary value. A survey on the world-wide crop loss annually due to plant diseases was summarized by Cramer (1967). The estimated total yield loss of cereal crops was 506.4 million tons, or 34.1 billion U.S. dollars. Crop losses, due to insect damage, was estimated at 5 to 10 percent of total crop values (4 billion dollars per year) (U.S. Dept. of Agric.-ARS, 1965). Plant diseases also cause estimated 10 percent (over 3 billion dollars) loss of foodstuff. At about the same time, crop losses in California, resulting from diseases, were estimated to be 247 million dollars (about 9.6%) with an acreage equivalent loss of about 9.4 percent (California Agric. Expt. Sta., 1965). The estimates of crop losses, such as those noted above, are not, for the most part, based on investigation and measurement. Most of them are based on surveys of opinions of persons working in the various crop areas (California Agric. Expt. Sta., 1965). It would, therefore, be difficult to assess the accuracy of this kind of report or to use the data in conjunction with estimates of losses from other sources.

Extensive research in the area of plant pests and disease control have greatly reduced both quantitative and qualitative losses. Methods of controlling pests and diseases can be categorized into two groups:

(1) cultural practices and biological control. Some control methods that are included in this group are: use of resistant varieties, eradication of diseased plants, clean culture, crop rotation, use of pest predators for pest control; (2) legal control. This includes quarantine and chemical control (Hughes and Metcalfe, 1972; Pfadt, 1971; Webster, 1972, Kenaga, 1970).

4. Summary

The plant growth and yield modifying effects of the following factors were reviewed: (1) light, (2) temperature, (3) water, and (4) wind. Some consideration was given to the effects of the soil and biological factors.

Visible light from the sun is used in photosynthesis and is the source of all the energy used by plants for growth and agricultural production. Many of the basic relationships between light and plant growth have been found in controlled environment studies where light is independently varied and other factors are held constant (Thorne, 1970). Photosynthesis of single leaves generally increases linearly with low light intensity but falls off and becomes constant at high intensity. The rate of growth and dry matter production of whole plants is more or less proportional to the light received (Phipps et al, 1975; Watson et al, 1972) or to the log of light intensity (Backman and Wilson, 1951).

Decreases in the intensity of light, reaching crops in the field, are mediated primarily by the degree of cloud cover. Variations in crop yield have been observed to result from variations in the amount of light received (Sibma, 1970; Watson et al, 1972). In some crops, certain stages of development are more sensitive to deficiencies in light intensity (Fischer, 1975).

The rate of growth increases approximately linearly with temperature between temperatures of about 5° to 30°C for temperate season crops. Growth stops at about 5°C and the rate usually decreases rapidly above an optimum of 25° to 35°C. Variations occur with plant species, age, and influence of other environmental factors.

One method of assessing the effect of temperature growth or development in the field is related to the sum of degree-days. A degree-day is the temperature above the minimum and below the optimum for growth in any day. The sum of degree-days may be closely related to maturity or vegetative yield (Arnold, 1959; Phipps et al, 1975). The second method relates growth and temperature by regression analysis usually in conjunction with other variables. Highly significant correlations have been found in some instances (Phipps et al, 1975; Haun, 1973).

Plant growth and crop yield are controlled by the available water supply (Begg and Turner, 1976). Some success has been had in attempts to describe this relationship for yield prediction by measuring the available water as rainfall (Williams, 1969), estimated soil moisture (Bair and Robertson, 1968) and evapotranspiration (Staple and Lehane, 1954b). Water potential has been used to estimate water availability in the laboratory (Boyer and McPherson, 1975), but is not useful for yield estimation.

The yield of crops is approximately proportional to the amount of water used by the crop (Arkley, 1963; Staple and Lehane, 1954b), although excessive water or periods of drought (Ashton, 1956) can cause temporary disruptions.

Individual crops have different water needs, and many crops have one or more developmental stages with particular sensitivity to water deficit, e.g., 14 days before flowering in wheat (Fischer, 1973; Salter and Goode, 1967). In crops where the economic yield consists of seed or grain, there is often greater resistance to water shortage than in crops where the production of leaves is important (Begg and Turner, 1976).

Plant growth is promoted by low velocity air movements (Wadsworth, 1959), but high velocity causes deleterious effects (Whitehead, 1957). The effects of wind have been little studied except in relation to windbreaks (Pelton, 1967).

Soils influence plant growth by limiting the availability of nutrient ions because of the location of the ions in the soil complex, the relative amounts of the different ions adsorbed, the soil ion exchange capacity, the diffusional ion flux and the mass flow of ions in the soil matrix (Milthorpe and Moorby, 1974).

Crop losses from biological factors, i.e., plant diseases, parasitic plants and insects, were recently estimated to equal about 10 percent of the crop (U.S. Dept. Agric. ARS, 1965). The estimates were based on surveys of various workers in the field.

B. AIR POLLUTION

The effects of the air pollutants on living systems have long been known as an important threat to the natural ecosystem. Much of the concern about pollutants stems from the resulting injuries to vegetation, especially to agricultural crops. Unlike the meteorological, soil, and biologicalfactors, air pollution is almost exclusively generated by men and their activities. The recognition of the sources of pollutants and their influences on the biosystem should therefore lead to the active pursuit of control standards and measures.

Although various definitions for air pollution exist, pollutants are generally considered as substances which, added in sufficient concentrations, produce a measurable effect on man, other animals, vegetation, or materials. Therefore, air pollutants may include almost any natural or artificial composition of matter capable of being airborne (Chambers, 1968).

Field surveys of air pollution injury on California agricultural crops have given an indication of the extent of the problem. Surveys suffer from the lack of a quantitative method of assessing losses. Most rely on subjective estimates from surveyors. The success of such surveys are therefore directly related to the competence of the surveyor. The first statewide survey (Middleton and Paulus, 1956; Middleton, 1961) estimated an 8 million dollar loss from smog damage. Another survey was taken in 1970 (Millican, 1971). Millican listed six pollutants, each with its percentage of the total observed plant injury: ozone (O_3) 50%, peroxyacyl nitrates (PANs) 18%, fluorides 15%, ethylene 14%, sulfur dioxide (SO_2) 2%, and particulates 1%. O_3 and PANs were most prevelent in the South Coast Air Basin. Fluoride is normally localized since it is normally emitted from stationary industrial sources. The amount of agricultural acreage located near fluoride producing industries is small. Ethylene injury is mainly associated with the cut-flower trade since it is generated from ventless or rusted heaters in heated glasshouses. SO_2 is also localized as it is normally emitted from stationary sources. Its emissions can be reduced through corrective measures of SO_2-discharging industrial plants. There has been only a single reported case (at El Dorado Co.) of lime particulate damage in this survey.

The most recent California survey on air pollution crop losses from 1970 through 1974 (Millican, 1976) shows an upward trend in economic losses (from 16.1 million dollars in 1970 to 55.1 million dollars in 1974). This trend is not necessarily correlated with increases in air pollution levels (for example, increases in planted acreage and crop value contribute to the increased loss estimate in 1973), but are more closely related to inflated market prices, an increasing inventory of susceptible crops and better methods of evaluating the effects of air pollution.

Since the responses of plants to air pollutants and their interacting environmental factors have been extensively covered in recent reviews (Mudd and Kozlowski, ed. 1975; Naegele, ed. 1973; Jacobson and Hill, eds. 1970; Taylor, 1974; Heck, 1968), only a general discussion is presented here.

1. Symptoms of Injury

Plant responses to air pollutants can be generally classified into three types: (1) visible injury symptoms, which are observed most distinctively on leaves. Normally these symptoms are observed as tissue collapse with necrotic patterns, chlorosis or other color changes, premature abscission; (2) growth responses, such as reductions in biomass, quantity of the crop yield; and (3) quality changes, such as, changes in nutritional content, color, texture, flavor, etc. of the product.

One of the most complete descriptions of visible air pollution symptomology can be found in a pictorial atlas by Jacobson and Hill (1970). The visible symptoms of acute foliar injury are somewhat specific for a given pollutant. The severity of injury varies from species to species, and depends on physiological leaf age, water status, and other interacting factors. Chronic injuries, associated with long-term or intermittent exposure to lower concentrations of pollutant, are less specific and often resemble symptoms of other environmental stress, senescence, insect and disease problems or nutritional imbalance. Visible symptoms of acute injury have been the principle means of identifying the effect of air pollutants on plants and in estimating pollutant effects on crop yield (Millican, 1971). However, pollutants may cause quantitative and/or qualitative changes in crop growth and eventual yield without any visible foliar injury (Heck, 1976).

a. Ozone

Ozone injury was first observed as stippling on grape leaves (Richards et al, 1958) and flecking on tobacco leaves (Heggestad and Middleton, 1959). Necrotic lesions were visible on the upper leaf surface as either red-brown pigmented stiple or bleached flecking. This pigmentation occurs in the mesophyll layers beneath the upper epidermis as a result of plasmolysis and eventual disintegration of palisade cells. Prolonged exposure or exposure to high concentrations of ozone extend the injury from palisade to spongy cells, producing bifacial necrosis. Chlorosis (Taylor et al, 1960) and pre-mature senescence (Engle and Gabelman, 1967) are commonly observed chronic injury symptoms. Small lesions may also coalese to form necrotic blotches (Heggestad and Middleton, 1959; Jacobson and Hill, 1970). Injury to conifers appears as tip burn (brown necrotic tips) with no clear separation between brown and green tissue. Chronic O_3 exposure causes chlorotic mottle, terminal die-back and abscission (chlorotic decline) (Miller et al, 1963).

The tip of the youngest leaves and the whole of the oldest leaves tend to be more susceptible to O_3. Reports have indicated that leaves ranging from about 65 to 95% of their matured size are most sensitive to

O_3 (Ting and Dugger, 1968). Mature plants in general are more resistant than young plants (Jacobson and Hill, 1970).

Reduced growth of some forest tree seedlings was reported after prolonged exposure to low concentrations of O_3 (Jensen, 1973). Growth and subsequent yield associated with O_3 damage are reported to significantly reduced in sweet corn (Heagle _et al_, 1972; Oshima, 1972), radish (Tingey _et al_, 1971) and tomato (Oshima _et al_, 1975). A yield reduction of as much as 50 percent was reported for citrus (Thompson and Taylor, 1969) and for potato (Heggestad, 1973). Crop composition was also reported to be altered by ozone (Pippen _et al_, 1975).

b. Peroxyacyl Nitrates and Nitrogen Oxides

Peroxyacyl nitrates are the best known of a group of compounds which result from photochemical reaction between nitrogen oxides and reactive hydrocarbons in the atmosphere. Peroxyacetyl nitrate (PAN) is the most abundant of this group and is responsible for serious plant injury in many polluted areas (Taylor, 1969). Another two members of the PANs group are peroxypropionyl nitrate (PPN) and peroxybutyryl nitrate (PBN). Although PPN and PBN are only found in trace amounts in heavily polluted air, they are several times more phytotoxic than PAN (Jacobson and Hill, 1970).

The injury induced by PAN varies with plant species, from a glistening appearance of the leaf undersurface to complete necrosis. In dicotyledon leaves, "silvering", "bronzing", "brown-black motting" may be found. Injury in monocotyledon leaves generally appears as transverse banding. The pattern of injury correlates with cellular differentiation and maturity (Noble, 1955; Glater _et al_, 1962).

Expanding leaves are much more sensitive to PAN injury than very young or old leaves (Taylor _et al_, 1960). Leaf injury in the fully expanded leaves and youngest leaves appears only at the base and the tip, respectively (Glater _et al_, 1962).

Inhibition of growth by PAN was reported in tomato and bean plants subjected to prolonged exposure of low concentrations of PAN (Jacobson and Hill, 1970).

Nitrogen dioxide (NO_2) is a product of combustion and certain industrial processes. In general, atmospheric NO_2 concentration is lower than the phytotoxic levels needed for plant injury. An accidental spillage or release causes relatively short but high-level exposure, which produces necrotic lesions and excessive defoliation (Jacobson and Hill, 1970; Taylor, 1973).

C. Fluorides

Of the various forms of fluoride existing in the atmosphere, gaseous hydrogen fluoride (HF) and silicon tetrafluoride are the main forms that cause plant injury because they are readily absorbed by plants. Fluoride accumulation over a long period of exposure also results in visual injury (Jacobson and Hill, 1970).

Acute fluoride injury in broad-leaved plants usually appears along the margins and tips of leaves as reddish-brown dying necrotic tissue (DeOng, 1946). In some leaves, the necrotic tissue may fall off, leaving a chewed appearance to the leaves. Occasionally streaking or spotting may occur. In monocotyledons, the necrotic area is at or near the blade tip, with clear darker banding separating tissue killed in succeeding exposure. Some may have intercostal streaking (Hitchcock et al, 1962). Fluoride accumulation in conifers results in brown or reddish-brown necrosis, beginning at the tips of needles and progressing toward the base. Chronic fluoride injury in general appears as loss of chlorophyll, resulting in a chlorotic or mottled pattern on the affected leaves (McCune, 1969).

It is interesting to note that the more resistant species or variety usually accumulates the most fluoride (McCune, 1969). In maize, plants that have past the elongation stage of development are most susceptible to injury and the degree of injury increases with the age of the leaves (Hitchcock et al, 1963).

Significant growth and yield reduction was reported in injured plants (Hitchcock et al, 1963). At very low HF concentration, the growth and vigor of young navel orange trees were greatly reduced even though easily distinguishable visible symptoms were absent (Brewer et al, 1960).

d. Sulfur Dioxide

Injury induced by SO_2 is the consequence of the conversion of SO_2 to sulfite and sulfate upon entry. The severity of injury depends on the rate of their accumulation and species tolerance. Sulfite is much more toxic than sulfate because of its reducing potential.

The leaf injury usually is initiated in the spongy mesophyll cells. Palisade cells are then affected. Acute injury in broad-leaved plants is characterized by initial dark-green, water soaked discoloration and, upon drying, bleached or pigmented marginal and intercostal necrosis (Linzon, 1965). The necrotic areas may fall out after a period of time. In monocotyledon species, necrotic streaks developed from near the tips and extended towards the base of the blades. Injury at the bend of the long leaf blade is most severe. The injury in conifers appears as brown necrotic tips of the needle, sometimes with a banded appearance as a result of a series of injurious exposures. Chronic injury in general resembles senescence (Jacobson and Hill, 1970; Taylor, 1973).

Fully expanded young leaves are first to show injury, while less mature expanding leaves are least affected (Jacobson and Hill, 1970).

Plant growth suppression by SO_2 has been reported. In alfalfa, Thomas and Hill (1937) demonstrated a reduction in carbon dioxide assimilation induced by SO_2. Cotton yield in terms of number of bolls was also shown to be reduced by SO_2 (Brisley et al, 1959). Growth and yield reduction by SO_2 was also demonstrated in radish (Tingey et al, 1971).

e. Ethylene and other Phytotoxic Pollutants

In general, the pollutants discussed in this section are of local concern. Ethylene and hydrogen chloride are by-products of combustion; chlorine and ammonia are waste products of industrial operations or accidental spillage. Heavy metals and industrial dusts from various sources very rarely cause extensive injury to crops (Darley, 1966); Jacobson and Hill, 1970).

Ethylene. Ethylene air pollution normally affects greenhouse operations most. The "dry sepal" injury in orchid (Middleton et al, 1956), and similar collapsed type injury in cotton (Hall et al, 1957) and in easter lily (Rhoads et al, 1973) were reported. Chronic injury is of more importance, and is the consequence of the growth regulating action of ethylene. This takes the form of retardation of normal growth, epinasty, chlorosis, necrosis, early abscission of plant parts and inhibition of flower opening (Taylor, 1973).

Hydrogen chloride. Hydrogen chloride causes marginal and interveinal necrosis and netrotic flecking on broad leaf plants. In conifers, tip necrosis of the needles is the only observed symptom of injury (Means and Lacasse, 1969).

Chlorine. Chlorine produces white to tan, irregularly shaped intercostal necrotic lesions, followed by bleaching and breakdown of the leaf tissue. Old and middle-aged leaves were most susceptible to chlorine injury. Abscission of leaves may follow chlorine exposure.

Ammonia. Brief exposure of plants to high concentrations of ammonia leads to development of sy ptoms in which, leaves may show a cooked green appearance and may stay green or turn brown on dying. Necrotic spotting and streaking, similar to SO_2 injury may occur but appear red or purple in color instead of bleached in appearance. Damage to storage fruits, namely, apple and peaches were also reported (Jacobson and Hill, 1970; Brennan et al, 1962).

Particulates. Particulates are not generally considered to be harmful to vegetation unless they are highly caustic or heavily deposited.

Heavy metals of general interest are: lead, manganese, zinc, nickel, boron, beryllium and cadmium. Lead adsorption on vegetation, associated with well-traveled roads, has been reported (Page et al, 1971).

Most of the studies on the harmful effects of cement-kiln dusts on vegetation describe the formation of a crust on plant parts in the presence of free moisture. Injuries may be induced due to the clogging of stomata, high salinity of the dust, and more specifically in California, the high pH of the dust-water mixture (Lerman and Darley, 1975).

2. Factors Affecting the Expression of Pollutant Damage to Plants

Plant sensitivity and the severity of injury produced by a pollutant is determined not only by concentration and duration of exposure, but also by environmental variables and biological factors.

a. Time - Concentration. Air pollution injury is a function of both pollutant concentration and time (Heck, 1968). However, the time-concentration (dose) parameter must be carefully utilized in describing exposures since equal doses may not produce an equal plant response. Plants normally have a greater response to higher concentrations and short exposure than to an equal dose of low concentration and long exposure periods. A time-concentration ozone reponse surface (Heck *et al*, 1966) and a model (Heck and Tingey, 1971) to predict acute foliar injury have been developed for some plant species. In a recent review, Heck (1976) lists time, concentration, injury-response equations calculated from this model for 19 types of plants which are divided according to O_3 susceptibility into sensitive, intermediate and resistant groups.

Multiple exposure is another area in which equal doses may not give equal responses. Studies on O_3 injuries have reported that, for a given dose, a greater plant response was el cited in a single continuous exposure than to two or more separated exposures of equal exposure time (Heck, 1968). Greater injury was found in pinto bean and tobacco subjected to continuous exposure than when the exposure was split into two time periods (Heck and Dunning, 1967).

b. Environmental Factors

Light. Three aspects of light: photoperiod, light quality and light intensity will be considered in this section.

Photoperiod. Plant sensitivity to photochemical air pollutants has been reported to be influenced by photoperiod. Reports indicate that plants were more sensitive to ambient oxidants and O_3 when grown under an 8-hour photoperiod than either a 12-hour or a 16-hour regime (Heck and Dunning, 1967; Juhren *et al*, 1957; Macdowal, 1965). The effect of photoperiod is particularly striking in relationship to PAN. Light is required before, during and after exposure for the development of PAN injury (Taylor et al, 1961). This photo-dependent relationship of bean and PAN injury was described in detail by Taylor (1969). Light affects O_3 plant sensitivity to a lesser degree. Ting and Dugger (1968) reported that cotton plants were no longer sensitive to O_3 after a 24 hours dark treatment. Longer pre-dark period (48 hours) was needed for O_3 protection in pinto bean and petunia (Taylor *et al*, 1961). With Virginia pine, however, 24 hours in the light prior to O_3 exposure protected seedling trees from injury while plants that were kept in darkness for up to 95 hours suffered injury (Davis and Wood, 1973). Pots exposure light was also found to affect the O_3 sensitivity. Extended dark periods following O_3 exposure delayed the development of symptoms in Virginia pine, until plants were placed in the light (Davis and Wood, 1973).

Light period-pollutant relationships appear to be sepcies specific. The mechanism of this relationship has not been identified and it remains an area requiring further study. Carbohydrate level within the leaves has been correlated with sensitivity (Dugger et al, 1962). Other possibilities such as stomatal interference have been discussed but no conclusion is yet available.

Light intensity. Taylor et al (1961) found in the pinto bean and petunia that sensitivity to PAN was increased by high light intensity (21.5 Klux) before PAN exposure, while the sensitivity to O_3 was increased by low light intensity (8.5 Klux) before O_3 exposure. Generally, plants are more sensitive to O_3 when grown at lower light intensities (Ting and Dugger, 1968; Dunning and Heck, 1973; Shinohara et al, 1974; Heck and Dunning, 1967). An exception was Bel-W tobacco (Heck, 1976).

Sensitivity to O_3, as light intensity changes during exposure, generally increases with increasing intensity. This was reported for tobacco (Heck, 1976) and pinto bean (Dunning and Heck, 1973) but the effect of light intensity (prior to and during exposure) on O_3 sensitivity was complicated by the interaction of relative humidity.

Light quality. The action spectrum of PAN injury to bean plants was studied by Dugger et al (1963). Maximal injury was observed at 420 nm and 480 nm, and less than half that at 640 nm. The sensitive spectral ranges closely resemble absorption spectrum of carotenoid. Shinohara et al (1974), working with tobacco, found that the O_3 injury was at its maximum under red light, followed by green, blue and far-red lights in decreasing order of sensitivity.

Temperature. The temperatures in which plants are grown, exposed and kept after exposure, are closely related to plant susceptibility to pollutant injury.

The plant susceptibility is influenced by day/night growth temperatures but appears to be species dependent. Macdowall (1965) reported that tobacco grown under a low day (21°C) and high night (32°C) temperature was more susceptible to O_3. Ozone susceptibility in Poa annua was greatest with 26°C day/17°C night temperature (Juhren et al, 1957). Again, no general trend exists as pollutant susceptibility varies with species (Heck, 1976).

Using three tobacco cultivars in Japan, Shinohara et al (1973) reported interactions between O_3 sensitivity, growth temperature, and post-exposure temperature. Plants grown at 23°C were more sensitive than at 13°C. Night temperatures had a greater effect on sensitivity than day temperatures. High post-exposure temperatures accelerated symptom development but low post-exposure temperatures rendered more severe injury. While low post-exposure temperatures caused increased sensitivity in tobacco and radish, the reverse is true for Virginia pine (Davis and Wood, 1973) and white ash (Heck, 1976).

The relationship between sensitivity and exposure temperature has been the subject of many studies. This relationship also seems to be variety or species dependent (Taylor, 1973; Heck, 1976). Contradictory data cloud a clear defination of this relationship. For example, in pinto beans, Heck _et al_ (1965) found that increasing exposure temperature causes decreased foliar injury. Dunning _et al_ (1974), on the other hand, indicated that increasing exposure temperature decreased foliar injury.

Relative humidity. Many of the studies on interactions of growth, humidity, exposure humidity and post-exposure humidity are summarized in a recent review by Heck (1976). In general, there appears to be a positive correlation between susceptibility to O_3 and increasing relative humidity. Tobacco and pinto bean plants were always more sensitive to O_3 when grown at 75% relative humidity (Heck, 1976).

Exposure humidity appears to have a similar relationship. This is illustrated with Virginia pine (Davis and Wood, 1973), pinto bean and Bel-W_3 tobacco (Otto and Daines, 1969). The exposure humidity also interacted with pre-exposure humidity (Dunning and Heck, 1973; Heck, 1976).

Many of the studies involving relative humidity have utilized values at extreme ranges. The definition of relative humidity-dose responses in plants has not been worked out within the realistic ranges normally encountered in ambient situations. Moreover, these studies were short-term in duration without adequate statistical designs.

There is no conclusive experimental evidence that relative humidity significantly affects susceptibility of plants to PAN, according to Taylor (1974) as long as conditions are such that the stomata remain open. However, little work has been done in this area.

Soil factors

Soil moisture. Soil moisture status prior to exposure is probably the least controversial factor that affects the susceptibility of plants to pollutants. Adequate soil moisture is essential to maintain maximum susceptibility. Tomato (Khatamian _et al_, 1973), pinto bean and tobacco (Seidman _et al_, 1965; Macdowall, 1965) subjected to water stress prior to exposure were found to be protected from O_3 injury. Similar findings were reported for beans and tobacco in response to O_3 and PAN. Observations of stomatal function showed that O_3 induced rapid stomatal closure in water stressed plants, while the closure in plants under optimal water availability was slow (Rich and Turner, 1972). Excessive soil moisture for an extended period of time may reduce susceptibility to O_3 due to impared root function under oxygen deficiency (Stolzy _et al_, 1961).

Soil type. Plants grown in heavy clay soils were less susceptible to O_3 than plants grown in vermiculite; similarly, plants grown in clay loam were less susceptible than plants in peat-perlite mix (Seidman _et al_, 1965; Heck and Dunning, 1967). Low oxygen tension was suggested to be one of the reasons for reduced sensitivity. Stolzy et al (1961) reported that the supply of oxygen to plant roots influenced the susceptibility of plants to oxidants. Plants growing in soils with an oxygen diffusion rate of 16 to 24 x 10^{-8}g.cm^{-2}.min^{-1} were completely protected from PAN and O_3 injuries, whereas at 34 to 90 x 10^{-8}g.cm^{-2}.min^{-1}, plants were moderately to severely injured by both PAN and O_3. This and a later study by Stolzy et al, (1964) on the root zone oxygen reduction in relation to apparent photosynthetic rate, carbohydrate concentration and susceptibility to O_3, indicate that for plants subjected to low root oxygen supply, the resulting accumulation of leaf carbohydrates rendered the plant protection from O_3 injury.

Nutrition

Salinity. Salinity (use of multiple strength of macronutrients) and moisture stress (by application of vacuum) were found to increase the resistance of sunflower plants to oxidant injury (Oertli, 1959). Yield reduction caused by O_3 was reported. It was found, that under high salinity, there was a smaller loss of bean pod yield from O_3 than with no salinity (Hoffmann et al, 1973). However, high salinity itself greatly reduced pod production whether or not O_3 was present. In a recent report, Hoffmann et al, (1975) found that -200 kPa (kilopascals) gave alfalfa protection from O_3 with no effect of salinity on biomass production. Therefore, it seems possible that salinity might increase production of some leaf crops grown in polluted areas.

Nitrogen. Among the soil nutrients that were studied in their relation to pollutant susceptibility, nitrogen has received most attention. Leone et al (1966) reported that in tobacco, nitrogen concentration that is optimal for growth (between 280 and 560 mg/l) also render maximal O_3 sensitivity. At two levels of nutritional nitrogen (ca. 60 and 300 mg/l), Ormrod et al (1973) also demonstrated that higher nitrogen caused greater magnitudes of dry weight decrease after O_3 treatment. Similar results were reported in Lemna (Craker, 1971). Conflicting results were reported by Macdowall (1965), in which he showed that O_3 susceptibility was enhanced by both deficiency (0.1 N) and excess (5 N) of nitrogen. Much of the conflict stems from different definitions of the "optimal concentration." Macdowall worked within a high nitrogen concentration range while the other studies were conducted at comparatively low ranges.

Other nutrients. The influence of soil nutrients other than nitrogen was reported, and there are apparent interactions between these nutrients. A summary of several studies on O_3 injury was provided by Heck (1976). Increased O_3 sensitivity associated with higher phosphorus concentration both in tissue and in the nutrient was reported (Leone and Brennan, 1970). Interaction between potassium and phosphorus was found in spinach and mangels (Brewer et al, 1961) and duckweed (Craker, 1971). In these, potassium increased O_3 injury at low phosphorus concentrations while at high phosphorus increasing potassium causes decreased O_3 sensitivity. High nutrient sulfur (32 mg/l) was reported to reduce the intensity of response of Blue Lake snapbean to O_3 (Adedipe et al, 1972). Increasing zinc was found to correlate with increased O_3 injury in pinto bean (McIlveen et al, 1975). Lemna plants growing on a nutrient medium lacking copper had significantly less O_3 injury than plants grown on a complete nutrient media (Craker, 1971). In this same study, Craker found no difference in O_3 response with plants grown in nutrient solution varying from one-tenth to half strength. This suggested that with balanced nutrient supply, plants may respond fairly uniformly to oxidant.

Modification of fluorine toxicity in tomato plants by altering nitrogen, calcium and phosphorus nutrition was reported by Brennan et al (1950). A deficient supply of these nutrients aided in preventing the absorption of a toxic amount of fluoride through roots or from fumigation.

Deficiency in either nitrogen or sulfur nutrition was found to decrease SO_2 susceptibility in tobacco and tomato (Leone and Brennan, 1972). An overabundance of nitrogen and sulfur tend to decrease and increase susceptibility, respectively.

Genetic factors. Air pollution susceptibility is known to vary among species, varieties and individuals. Breeding new air-pollutant resistant varieties has been carried out on a limited scale to reduce adverse effects of air pollutants.

A list of crop, ornamental, and forest species, in which variation in sensitivity to various pollutants has been observed, was given by Ryder (1973). Lists of species susceptibilities to O_3 and of cultivars responses to oxidants, O_3 and PAN were given by Heck (1976).

Pathogen interaction. A summarized review by Manning (1975) on the interaction between the effects of air pollutants and plant associated fungi, bacteria, and viruses provided information in this sphere of research. Plants that are injured by O_3 appear to be more susceptible to invasion by facultative parasitic and saprophytic fungi, while the O_3-injured host tissues tend to retard obligate parasitium by fungi. Ozone-injured leaves of potato (Manning et al, 1969) and geranium (Manning et al, 1970) were reported as more susceptible to Botrytis infection than non-injured leaves. Experiments with obligate parasites showed fewer infections by urediospores, decreased hyphal growth, and uridiospore production by wheat stem rust fungus, when plants were exposed to O_3 (Heagle and Key, 1973a).

Plant responses to oxidants in the presence of pathogens were also studied. Yarwood and Middleton (1954) first observed that rust-infected bean and sunflower leaves were less injured by Los Angeles Basin smog than were healthy leaves. Generally, pathogen invaded leaves are less susceptible to O_3 injury. This was illustrated in rust-infected wheat (Heagle and Key, 1973b) and in Botrytis infected broad bean (Magdycz and Manning, 1973). It was suggested that the apparent protection may be due to some diffusible substance emanating from the point of infection. Pinto bean leaves infected by common mosaic virus were also reported less sensitive to O_3 injury (Davis and Smith, 1974). Kerr and Reinert (1968) found that red kidney bean leaf areas infected by Pseudomonas are protected from O_3 injury.

In connection to the above discussion, it is interesting to note that fungicide benomyl was shown to reduce O_3 injury in bean cultivars (Manning et al, 1974).

Field observations showed that leaf and needle diseases decrease in incidence near the source of sulfur dioxide. Sulfur dioxide was reported to decrease the incidence and severity of bean rust and also affect the size and percentage germination of uridospores (Weinstein et al, 1975). Accumulations of hydrogen fluoride above the field level were found to decrease disease in bean and tomato (Manning, 1975).

Pollutant combinations. Combinations of two or more pollutants are commonly monitored in a polluted atmosphere. Menser and Heggestad (1966) first reported the synergistic response of tobacco plants to combination of SO_2 and O_3. To date, a great portion of studies on plant responses to mixtures of pollutants is of SO_2 and O_3 combinations.

SO_2 and O_3. Menser and Heggestad (1966) first noted that mixtures of O_3 and SO_2 caused foliar injury to tobacco at concentrations which were nonphytotoxic when fumigated singlely. Ozone and SO_2 synergism was also reported with eastern white pine (Dochinger et al, 1970) tobacco (Macdowall and Cole, 1971) and peanut (Applegate and Durrant, 1969). Tingey et al (1973) studied the foliar injury responses of eleven plant species to O_3 and SO_2 mixtures and concluded that the foliar injury resulting from mixtures was dependent on both the plant species and gas concentrations.

The effect of O_3 and SO_2 mixture on growth and yield have also been reported. In contrast with the synergistic foliar injury, Tingey and Reinert (1975) reported that in tobacco chronic exposures to gas mixtures resulted in growth reductions that were equal to the additive effect of single gases exposures. They also found a less than additive response in alfalfa and no difference in response between the mix and single gases in radish. Heagle et al (1974) also reported no significant difference in soybean growth and yield responses to O_3 alone and to mixture of O_3 and SO_2.

SO_2 and NO_2. Tingey et al (1971) reported that although high concentrations of NO_2 and SO_2 (200 and 50 pphm respectively) alone caused no visible leaf injury, injury did develop when plants were exposed to mixtures of 5 to 25 pphm of each of the two gases. Apparent photosynthetic rates of alfalfa plants were found reversibly depressed more effectively by SO_2 and NO_2 mixture than by SO_2 alone and at NO_2 concentration well below those normally causing any inhibition (White et al, 1974). The synergestic effect was most marked at the low concentrations and decreased as concentrations increased. However, in a recent report, Bennett et al (1975) could not find the synergistic response at low NO_2 and SO_2 combination concentrations. Instead, they indicated from their results that relatively high doses were required to cause the enhanced phytotoxicity of SO_2 and NO_2 in combination.

In field studies on native desert vegetation, Hill et al (1974) did not find synergism of plant injury in plants treated with NO_2 and SO_2 combinations. Studies by Skelly et al (1972) of eastern white pine located near a source of oxides of nitrogen and SO_2 were also non-conclusive of the interaction of pollutant combination.

Fluoride and SO_2. Studying the influence of a sulfur dioxide and hydrogen fluoride combination on the growth and development of citrus, Matsuchima and Brewer (1972) reported an additive effect of HF and SO_2 in Keothen sweet orange and no significant difference in linear growth in HF and SO_2 applied singlely or combined. Mandl et al (1975) found that growth of barley, corn, and bean shoots were also not affected by HF and/or SO_2 treatments. However, they reported that at low SO_2 concentrations (0.06 to 0.08 ppm), foliar response of barley and corn was accentuated by the combination of SO_2 and HF.

Cultural practices. The severity of air pollution injury and damage to agricultural crops can be reduced by proper cultural practices. The understanding of the various factors discussed in this section of pollutant interaction (Section B.2.), namely meteorological, edaphic, genetic and other factors can be applied in practices which change the susceptibility of crops. A review by Ormrod and Adidipe (1974) presented suggestions in this regard. Cultural practices that can change pollutant susceptibility are: application of fertilizer, pesticide, herbicide and other chemicals, irrigation, selection of resistant cultivars as well as resistant crops, and planting schedules.

3. Summary

Plant injury has been attributed to a number of different air pollutants, most notably ozone, peroxyacyl nitrates (PANs), fluoride, ethylene, sulfur dioxide, and particulates. The photochemical oxidants (ozone and PANs) are more widespread. The other pollutants are usually from industrial sources and effects are more localized.

Plant responses to air pollutants may be: (1) visible injury systoms, (2) growth responses, and (3) metabolic changes, with resultant differences in nutrition, flavor, etc. The symptoms of acute injury may be characteristic for a specific pollutant but may be produced by other agents. In acute injury, necrotic patterns on leaves result from collapse and death of cells. Chronic injury is associated with chlorosis or other color changes which may eventually result in leaf necrosis or abscission and is less characteristic for the toxic agent.

Ambient oxidants in some areas of the United States do clearly cause growth and yield reductions in some agricultural crops. Reported yields in nonfiltered field chambers were reduced compared with those in filtered chambers by up to 50 percent for citrus, potato, tobacco and soybean, up to 60 percent for grape and up to 29 percent for cotton.

Plant responses to air pollutants are subject to variations from environmental and genetic factors, distribution of exposure to pollutant and presence of pollutant mixtures. There is a distinct variation in susceptibility to air pollution among plant species, varieties, and individuals.

Plant injury responses are a function of pollutant concentration and time, but the response to a given dose is frequently greater if presented in a shorter exposure time. Plants generally are more sensitive when grown under a short photoperiod, medium temperature, and adequate soil moisture. Low light intensity increases sensitivity to ozone and decreases sensitivity to PAN. Plants grown at low temperature prior to exposure or under dry conditions are more resistant. Usually high humidity increases susceptibility to ozone. Low root oxygen and high salinity may reduce plant growth and ozone sensitivity. Ozone and sulfur dioxide are most studied in pollutant mixtures, but in some, NO_2 or fluorides were added. Plant responses have been varied. Additive, less than additive and greater than additive effects have been reported.

C. PRODUCTION ESTIMATES

1. General Problems

a. Economic Yield Criteria

For the purposes considered in this review, it would be desirable to have crop production expressed in terms of the economically valuable yield of the crop. Unfortunately there is no uniform criterion for deciding what constitutes yield among the workers, in various fields, who attempt to find functional relationships between crop production and environment. Of course this non-uniformity results largely from the fact that there are different aspects of the crop-environment response being studied. For example, those investigating basic relationships in photosynthetic production often report production as net assimilation rate (g $m^{-2}day^{-1}$), relative growth rate (g $g^{-1}day^{-1}$) or as CO_2 uptake (g $m^{-2}hr^{-1}$). It would not usually be advisable to use factors obtained in such studies to calculate assessments of environmental effects on annual crop yields. Nevertheless, such a procedure might be necessary when no other data are available.

If economic gain or loss is taken as the desirable criterion on which to base production estimates, it is obvious that it is not easily applied uniformly in experimental studies. In determining air pollution damage, leaf injury estimates are the most common means of assessing the degree of injury, but as has been pointed out more than once, economic loss is not always closely related to leaf damage (Brandt and Heck, 1968; Westman and Conn, 1976). Bronzing of leaves or other superficial injury to some leaves could result in a complete economic loss of a crop such as lettuce without causing measurable changes in leaf weight. In other cases, the assessment of loss on the basis of visible leaf injury may, on the contrary, overestimate the economic loss, since photosynthetic production from the total leaf surface of the plant is sometimes not required for full yield. In a study of defoliation effects on yield, for example, Jones et al (1955) removed 50 percent of sugar beet leaves (at the 4th and 8th leaf stage) and found no reduction in yield of roots or of sugar content.

b. Estimations

The effects of environmental factors on crop yield may be defined by correlating yield variations with variations in environmental factors. This approach can also be utilized in defining the relationship with diseases, pests, and air pollutants.

Crop yield is normally reported in terms of yield per unit land area. Estimates of the effect of an environmental variable on yield may be expressed in terms of the amount of yield per unit change in the variable or as the percentage yield increase or loss per unit change of the variable.

It would be preferable to determine the effects of various environmental variables on crop yield by the use of properly constructed controlled environment chambers that keep all non-experimental variables uniform. Unfortunately, chamber environments are not representative of ambient conditions and experimental results from growth chambers cannot be presumed to be valid for field conditions.

Problems arise when the attempt is made to determine the relationship between yield and environmental variables in the field. This normally occurs because of the number of interacting factors present which influence plant growth and yield. A few variables such as soil type and cultural procedures can be controlled but the majority of meteorological variables cannot. Even when several factors are controlled by an apparatus such as an open top chamber, the alteration of other ambient conditions normally produced significant changes in plant growth and yield (Heagle *et al*, 1973). It is doubtful whether artificial environmental factors can be manipulated to duplicate ambient variations. This is not to suggest that such approaches should be abandoned. Valuable data have been obtained using such procedures and their validity may not be surpassed by other methods (Thompson and Taylor, 1969; Earley *et al*, 1966).

The alternative method to experimentally varying environmental factors is to measure existing outdoor variations and statistically test their impact on yield responses. This method also is not without problems. A few of these are listed below:

(1) Factor correlations. In the field, some variations of factors such as high radiation and high temperature often occur at the same time, especially if measurement is for a relatively short time period, e.g., the summer growing season. When factors tend to be correlated in this way, it is difficult to determine reliable coefficients by regression analysis or to obtain accurate estimates if functions are used to predict yield.

(2) Limitations of static models from regression analysis. Functions relating environmental factors to yield depend on the range of variation shown by each during the period over which the correlation was made. The model function could only be applied within the ranges of the variables used to develop it. In an arid climate with almost continual sunshine, for example, it would not be possible to determine the effects on yield for radiation variations not included in the tested data set. The effects then, of unusually cloudy weather could not be predicted from the developed equations. Robertson (1974) indicated that weather patterns in Canada were changing in recent years making previously developed yield predictive functions inadequate.

(3) Subjective assessments. Some factors which can influence yield are hard to measure quantitatively both with regard to the factors themselves and also the influence on yield. Some plant diseases and insect pests are examples. If they are assessed, it must be done by field surveys and this is subject to all the uncertainties associated with that method (Anonymous, 1965).

2. Field Surveys

Field surveys for estimating air pollution-related crop damage are normally conducted by well trained crop survey reporters. This method is by its nature strongly dependent on the judgment of these survey reporters, as they make on-the-spot investigations of each air pollution episode, usually based on visible symptoms (Waddell, 1974; Millican, 1971). The range of information in such reports, normally include: county, location, suspected pollutant, crop variety, acreage affected, data of incidence, average percentage of each plant affected, average percentage of plants affected, loss in quantity or quality, and estimated crop loss (Laccasse and Moroz, 1969).

Economic losses to an agricultural crop were extropolated from an estimated yield loss, often using the "rule-of-thumb" (Millican, 1971). In this, the observed visible injuries are related to yield loss by various indices, i.e., 1 to 5 percent leaf injury resulted in 1 percent dollar loss, 6 to 10 percent leaf injury in 2 percent dollar loss, 11 to 15 percent injury in 4 percent dollar loss, and so forth. In cases such as citrus and grapes in California, where experimental data are available concerning productivity reduction as a result of photochemical smog, the assessment estimates were adjusted according to the degree of ambient smog (Millican, 1971). In the event of total crop distruction, the loss was sometimes calculated as the cost of replacement at the prevailing market price (Pell and Brennan, 1975).

The first state wide survey was made on an experimental basis in California (Middleton and Paulus, 1956). The survey covered four categories of crops (field, flower, fruit, and vegetable) and one of weeds. Similar programs were established in Pennsylvania, New Jersey and New England states. In total, air pollution losses in Pennsylvania for 1969 were estimated at approximately \$11 million (Weidensaul and Lacasse, 1972). In New Jersey, \$1.2 million was estimated as the losses on agricultural crops and ornamental plantings in 1971 (Feliciano, 1971). Similar loss (ca. \$1.1 million) was evaluated for New England between 1971 and 1972 (Naegele et al, 1972). It is interesting to note that great annual variations in estimated air pollution damage exist. For example, a 98% reduction was observed in Pennsylvania between 1969 and 1970 (ca. \$11 million and \$225 thousand, respectively) (Weidensaul and Lacasse, 1972); a 89% reduction in New Jersey between 1971 and 1972 (ca. \$1.2 million and \$128 thousand, respectively) (Pell and Brennan, 1975). As discussed previously in I, B.2., various factors are responsible for the sensitivity of plants to air pollutants. Among the environmental factors, Pell and Brennan (1975) attributed the reduction in yield loss mainly to the unusual rainfall pattern in 1972.

3. Production Functions

a. Environment-Yield Relationships

Crop production has been related to weather data on many occasions. The objective in these studies is in some cases to produce an equation which will estimate the yield effect of weather factors in any given year (Thompson, 1962, 1963; Staple and Lehane, 1954a; Lomas, 1972). At other times, studies have been designed for development of mathematical models which will predict the dry-matter weight as a function of the environmental parameters over intervals of time as short as one day and to provide evaluations of the status of the crop throughout the growing season (Haun, 1973; Baier, 1973; Splinter, 1974). Attention here will be directed primarily to studies of the former type.

The field environment is generally characterized by complex variations and interactions among the climatic factors. Therefore yields cannot usually be expressed in terms of functions with only one independent variable. More often a response function is obtained by multiple regression of more than one variable.

Progress is being made in the analysis of the complex relationship between weather and crop development and crop yield (Baier, 1973; Stanhill, 1973; Shawcroft et al, 1974). Most of the studies relating weather factors to crop yield can be divided into one of three groups depending on the approach used. One approach has been the straight forward statistical analysis of the growth or yield in terms of weather data. A second approach uses the soil water status or soil moisture estimates calculated from the weather data and characteristics of the soil under consideration. In the third approach evapotranspiration estimates are related to yield. Combinations of these approaches are also used at times.

Estimates from weather data. Crop yield has frequently been studied in relation to a single climatic factor with varying degrees of success. Dermine and Klinck (1966) attempted to relate yields of oats in eastern Canada to precipitation or temperature. They found low and not significant correlations in the analysis. Lomas and Shashoua (1973) reported the yield of wheat in three semiarid sampling areas of Israel was linearly related to unusual rainfall according to the equation:

$$Y = -27.2 + 0.599X$$

with Y in KG/1000 M^2 and X in mm of rainfall. The correlation coefficient was small (0.154) but significant at the 1% level.

The production of three varieties of corn grown for forage during one season in Britain was separately related to accumulated temperature, Ontario heat units or solar radiation by Phipps et al (1975). Cubic regression equations were developed for temperature, heat units, and radiation to predict continuing dry matter production of each variety during 150 days of growth. An average of 94.9 percent of yield variation was accounted for by those variables.

Staple and Lehane (1954a) determined that the yield of wheat in Canada over a number of years was fairly closely correlated with precipitation. Simple linear regression accounted for 62 percent of annual yield.

One of the most widely used methods of statistical analysis of crop weather relations was developed by Fisher (1924). Fisher analyzed wheat yields obtained over 60 years at Tothamstad England by multiple regression techniques. The rainfall of each year was divided into 61 periods of 6 days and was fitted to a fifth-degree polynomial on time. A trend variable was included for yield changes due to non-weather causes. Little correlation was found between yield and rainfall. Buck (1961) used the same techniques and data as Fisher, but in addition to rainfall and temperature, a term for actual transpiration was calculated. There was still no significant correlation between wheat yield and rainfall and transpiration, but when the method was applied to sugar beets, 73 percent of annual yield was accounted for.

Some of the most successful analyses of yield and weather have been done by Thompson (1962, 1963, 1964). Using annual crop yield data from a number of states of the mid-west and Plains areas of the United States, Thompson calculated equations by multiple curvilinear regression analysis for weather effects on annual yield of wheat (Thompson, 1962), corn, soybeans (Thompson, 1963) and sorghum (Thompson, 1964). Standard weather data were used to find averages in each state for monthly temperature and rainfall during the growing season and preseason precipitation. A factor for trend due to technologically related yield increases was included in each analysis. In most of the calculations, correlation coefficients were 0.90 or greater.

An example, in Table 1 shows the multiple regression coefficients and constants found for the relation of corn yields to weather in Illinois, Indiana, Iowa, and Missouri (Thompson, 1963). It can be seen that regression coefficients vary between states and only apply to the area for which they are calculated.

Similar statistical analyses have been successful when they were applied in semi-arid regions (Gangopadhyaya and Sarker, 1965; Lomas, 1972; Lomas and Shashoua, 1973). In India, Das and Madnani (1971) used multiple regression analysis and long-term records of weather and yields. The equation derived for final yield (Y) of rice was:

$$Y = 430 + 33.7\ X_2 - 49.7\ X_3 + 9.65\ X_4$$

where X_2 = the number of rainy days in July; X_3 = the number of times of drought in August and X_4 = the number of rainy days during the last half of September. The multiple correlation coefficient was nearly 0.90. Similar techniques were used for other rice growing areas of India, and was found that other weather elements were important as predictors (Robertson, 1975).

Estimates from soil moisture status. Since standard weather data and multiple regression analyses sometimes have not adequately explained crop-weather relationships, some workers have designed ways of using soil moisture to estimate crop growth and production. Long-term soil moisture records are not readily available, and therefore, methods have been developed for estimating soil moisture from standard weather data (Dale and Shaw, 1965; Baier and Robertson, 1966; Baier, 1967).

Baier (1973) concluded that "a realistic crop-weather analysis model

Table 1. Constants (a values) and multiple regression coefficients (b values) for years and weather variables and their relation to corn yields in five states (after Thompson, 1963).

	Illinois	Indiana	Iowa	Missouri	Ohio
			Constants (a values)		
	-3072.84	-2454.18	-3223.10	628.62	-2269.80
		Regression Coefficients (b values)			
X_1	.8069	.8605	.7045	.7012	.9472
X_{2_2}	1.0263	.5248	3.7065	- .6489	3.1553
X_2	- .0134	- .0165	- .0773	.0143	- .0637
X_{3_2}	-19.9559	----	----	-12.0473	----
X_{4_2}	-91.1648	-39.9844	-18.3570	-79.6712	-8.4442
X_4	.8194	- .3249	.5067	.5437	.6745
X_{5_2}	3.4943	8.5441	48.0467	-24.1244	16.3843
X_5	- .0562	- .0781	-.3464	.1334	- .1186
X_{6_2}	17.2262	52.7694	-81.4565	-40.1511	-20.6316
X_6	- .2354	- .5343	1.6797	- .0247	-1.2751
X_{7_2}	3.6315	12.5574	25.0782	16.4336	-1.2856
X_7	- .0316	- .0786	- .1851	.0892	- .0022
X_{8_2}	107.0276	104.2592	-8.7055	14.9916	19.6940
X_8	- .2296	-1.6697	- .3593	.1427	- .5797
X_{9_2}	92.6869	43.2209	22.7112	41.4311	49.7832
X_9	- .5818	- .2673	- .1697	- .2680	- .3477
X_4X_5	1.1520	.5945	.1597	.9905	.0355
X_6X_7	- .1665	- .6065	.9431	.5496	.4590
X_8X_9	-1.3963	-1.2351	.1598	- .2177	- .2021

The F values for analysis of variance: Illinois 32.2, Indiana 17.8. Iowa 17.5, Missouri 29.0, Ohio 16.1.

X_1=year, X_2=preseason precipitation, X_3=May temperature, X_4=June rain,

X_5=June temperature, X_6=July rain, X_7=July temperature, X_8=August rain,

X_9=August temperature.

Total degrees of freedom = 32. One degree of freedom is assigned to each regression coefficient. With 20 degrees of freedom for regression and 12 degrees of freedom for residuals an F value of 3.86 would be significant at 99% level of probability.

must account for the daily interacting effect of at least temperature, soil moisture, and an energy term." For the "versatile soil moisture budget" of Baier and Robertson (1968), daily estimates of precipitation and evapotranspiration were required. To calculate the soil moisture using the VB, it was necessary to know the moisture tension characteristics of the soil, and this was obtained by analysis of the particular soil throughout the root zone.

The soil-water balance method was found to provide a better estimate of wheat yield than multiple regression on climatic data (Baier and Robertson, 1968).

Using wheat yields from three regions of differing rainfall in Israel, Lewin and Lomas (1974) analyzed the data by (1) multiple regression, (2) principal components (Richard and Pochop, 1975; Kendall, 1957), (3) Fishers method, and (4) by a soil moisture simulation technique. The moisture simulation technique gave the best results under all rainfall conditions. Both the simulation model and the statistical methods gave good results in the arid zone, each accounting for more than 70 percent of yield variation. The higher the rainfall amounts, the lower was the predictive accuracy for all of the analysis methods.

Estimates from evapotranspiration. Evapotranspiration (ET) is used as an agroclimatic index which accounts for plant factors in addition to weather variables, and it has been widely used to assess the effects of water and energy supply on growth and yield. ET has also been used to estimate the consumptive water use of crops for determining when and how much to irrigate (Haise and Hagen, 1967).

Annual wheat yields and annual evapotranspiration among two sets of field plots in Canada were curvilinearly related in a study by Staple and Lehane (1954a, b). The resulting curves corresponded to the equations:

$$Y = 0.26\ M^2 - 2.10\ M + 8.7 \quad \text{and}$$

$$Y = 0.40\ M^2 - 3.09\ M + 5.63$$

where M = evapotranspiration in inches and Y = yield in bushels per acre. The multiple correlation coefficients were 0.847 and 0.876 respectively.

Williams (1969) also analyzed the effects of weather on wheat production, including the entire Canadian prairie wheat crop between 1952 and 1967. By using a complex system of analysis, multiple regression equations were derived for yield based on precipitation or on both precipitation and potential ET. The average deviation of yield estimates was 13 percent in the first case and only 7 percent with the potential ET included.

Penman (1962) used ET values computed from climatological data in analysis of results from irrigation experiments in southern England. Accumulated dry matter production of grass was linearly related to ET over a period of six years. There were only small deviations from the slope due to winter temperatures.

A linear relationship was also found by Smith (1960) for the relationship between ET and hay yields in England from 1939 to 1956. The equation describing this relationship was:

$$Y = 7.05 + 1.56\,T + 0.27\,N$$

where Y is yield in hundreds of pounds per acre, T is inches of ET and N is the number of years after 1946. The average annual deviation from the predicted value was 2.1 percent.

Grain sorghum was grown in irrigated experimental plots at Davis, California. Stewart et al (1975) found that the annual grain yield from these plots was proportional to the seasonal total of ET. The regression of grain yield on total ET resulting from various irrigation programs gave the equation:

$$Y = 541 + 144.8\,ET$$

Y was in KG/hectare and ET in cm of water.

b. Air Pollution Loss Functions

This section is concerned with pollution-economic loss functions for vegetation and with crop-loss functions which can be readily converted to economic loss.

Although it is well recognized that results from controlled chamber studies rarely apply directly to field conditions, nearly all of the air pollution-plant damage functions have been derived from controlled chamber environments (Heck et al, 1966; Heck and Tingey, 1971; Westman and Conn, 1970). These studies suggest that the results, at least as general relationships, apply to ambient field conditions, and the functions have been used in yield loss estimates (Millican, 1976; Benedict et al, 1973).

Heck (1976) took data from 74 references on percentage leaf injury from acute (to 8 hours) ozone fumigations and calculated response equations for 19 kinds of plants. These were based on the equation of Heck and Tingey (1971):

$$C = A_o + A_1 I + A_2/T$$

in which C = concentration of O_3 in pphm; I is percent response; T is time in hours; and A_o, A_1, and A_2 are constants (partial regression coefficients) that are specific for pollutant, plant species and environmental conditions used.

The relationship of foliar injury to economic yield remains obscure in this and other studies where damage is recorded as percentage foliar injury. Heck (1976) did compare the foliar injury response and the growth reductions of 12 plants or varieties as recorded in several studies. The ratio of percent growth reduction to percent foliar injury average 1.17, indicates a close correspondence. However, among the 12 plants, it would not be possible to relate the vegetative growth response to the yield of a salable crop with the possible exception of tobacco. The research with ozone or other oxidants which would make it possible to assess economic loss from leaf injury has not been done.

In some work using plants fumigated with sulfur dioxide in small field plots, the relationship between destroyed leaf area and yield was investigated for some crops. The relationship was linear between the percent of leaf area destroyed and yield as percent of control for alfalfa (Hill and Thomas, 1933), wheat (Brisley and Jones, 1950) and cotton crop (Brisley _et al_, 1959). The equation for alfalfa was:

$$Y = 98.6 - 0.263\ X$$

following a single fumigation and

$$Y = 96.6 - 0.754\ X$$

after 3 fumigations, where Y = percent of control yield and X = percent of leaf area destroyed. The amount of yield loss for one percent foliage destroyed varied from 0.26 to 0.62 percent for wheat and was reported as 0.68 percent for cotton.

In what seems to be the only case in which an ozone dose-response function has been made for a crop under approximately ambient field condition, Oshima (1975, Oshima _et al_, 1976) has developed a method for producing crop yield-loss functions in relation to seasonal ambient ozone levels at a number of sites in southern California. The seasonal O_3 doses were calculated from hourly averages obtained from Air Pollution Control District monitoring stations.

Only one O_3 dose-yield response function for alfalfa has been issued to date (Oshima et al, 1976). The O_3 dose-alfalfa yield function was:

$$\text{percent yield reduction} = -1.068 \times 10^{-4} + 9.258 \times 10^{-3}$$

Dose is pphm-hrs ozone. Oshima's method offers the most direct method of crop loss assessment yet available, though it is apparent that further development and more data are needed.

A comprehensive model was developed by Stanford Research Institute (SRI) (Benedict _et al_, 1971, 1973) to estimate air pollutant damage to vegetation throughout the United States. Pollutant estimates were based on emissions of hydrocarbons, sulfur dioxide, and fluorides in the most populous counties, those in designated Standard Metropolitan Statistical Areas (SMSA's), where fuel consumption and emission sources were greatest. Of all counties in the United States, 687 were selected as having potential plant-damaging exposures of pollutants. Pollution potentials were calculated for counties in SMSA's from the following equations:

Oxidants

Emissions(1) x concentration rate factor(2) x area(3) x episode days(4) = pollution potential (9 classes)

Sulfur dioxide

Emissions x concentration rate factor x area x episode days = pollution potential (6 classes)

Fluorides

Emissions from various types of large single sources = pollution potentials (4 classes)

The pollution potentials were used in these formulas for calculation of dollar loss:

crop value x crop sensitivity x pollution potential = dollar loss

ornamental value x ornamental sensitivity x pollution potential = dollar loss

The pollution potentials were divided into classes such that in descending order each lower class was about one-half that above, i.e., class 7 was about half of class 8 and double that of class 6. The loss factors were also arranged in a given sensitivity class so that the factor for each lower class was half that above, e.g., the highest loss factor in class 8 was 0.400 and in class 7 was 0.200.

A number of approximations and subjective judgements were used in this method of loss estimation. For example, the relative sensitivities of the 65 plant species used in the study were based on many sources of information, and in some cases, the sensitivity was not known or represented subjective opinion. The sensitivity indices were based largely on foliar injury data with little input from yield data. The assumption that the pattern of the pollutant dose-yield response curve is the same for each plant is no doubt inaccurate. There is no way presently available to test the accuracy of the SRI loss estimates. With so many unverified assumptions in the method the values obtained may not be presumed to have great accuracy.

Another function for assessing damage to vegetation was developed by the Midwest Research Institute (Liu and Yu, 1976). Five meteorological variables to account for weather effects were included in the function. This method used pollution potential indices and data for value of vegetation and vegetation loss from the SRI study. Coefficients were calculated by step-wise linear multiple regression for 12 crop categories in 74 counties for which useable weather data were available.

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(1) Tons of hydrocarbons or oxides of nitrogen emitted per square kilometer per day.

(2) a factor indicative of the tendency of climatic conditions to concentrate pollutants during an air-stagnation period.

(3) Square of the radius of the SMSA, assuming the area as circular.

(4) Percentage of days during the growing season occurring in stagnation periods of two or more successive days.

The equation used and the key to variables are as follows:

$$CROPL_i = a + b\ CROPV_i + c\ TEMB + d\ TEMA + e\ SUN + f\ RHM + g\ DTS$$
$$+ f\ SO_2 + g\ OXID$$

where $CROPL_i$ denotes the economic loss (in $1000) of the ith type of crops by county from the Benedict (SRI) study.

Table 2 lists the variables used in the economic damage functions. The damage functions resulting from the regression analysis are shown in Table 3 for 10 crop categories using pollution severity indices. The numbers below the regression coefficients are standard errors with (*) indicating that they are significant at the 1 percent level.

Estimated economic damages from pollution for all crops were shown by Liu and Yu (1976) for the 74 counties where appropriate data were available throughout the United States.

It appeared that the model worked well for oxidant damage to vegetation in that highly significant correlation coefficients were obtained for some of the multiple regression variables. Other variables appear to be non-significant and have high variances. The greatest deficiency of the model is the lack of an objective standard against which the calculated estimates may be compared.

4. Discussion

a. Agricultural Yield Loss Function

The discussion emphasis will be directed to consideration of methods and data available for development of air pollutant dose-vegetation loss functions.

The focus of attention will be directed toward California, and particularly those areas of the state where the greatest pollution losses occur.

The question to be considered first is, what is the best method of assessing the loss of agricultural yield resulting from air pollution?

The most widely used method for making crop loss assessments has been to use "on the spot" surveys in which field observers estimate vegetation injury from visible symptoms and yield loss from subjective judgment. The

Table 2. Variables used in economic damage functions (from Liu and Yu, 1976).

A. Dependent variables - vegetation loss (in $1,000)

CORNL	Corn grain loss
SOYBL	Soybean loss
COTNL	Cotton loss
OVGTL	Other vegetable loss
NUSRL	Nursery loss
FLORL	Floral loss
FRSTL	Forestry loss
FCROL	Field crops loss
FRNTL	Fruit and nuts loss
VEGTL	Vegetable loss
TOCRL	Total crop loss
TOORL	Total ornamentals loss
ALPLL	All plant loss

B. Explanatory variables

CROPV	The value of the vegetation in question (in $1,000)
TEMB	Number of days with temperature 32°F or below
TEMA	Number of days with temperature 90°F or above
SUN	Possible annual sunshine days
RHM	Relative humidity
DTS	Number of days with thunderstorm
SO_2	Annual mean level for sulfur dioxide (ug/m^3).
OXIDE	The relative plant-damaging oxidant pollution potential index
CSO_2	The relative plant-damaging sulfur dioxide pollution potential index.

Table 3. Economic damage functions on vegetation with pollution relative severity indices ($1,000) (from Liu and Yu, 1976).

	a	CROPV	TEMB	TEMA	SUN	RH1	DTS	CSO_2	OXID	R_2
(1) CORNL	4.4 (32.1)	0.001 (0.001)	0.02 (0.04)	0.09 (0.10)	-0.13 (0.35)	0.16 (0.34)	-0.041 (0.10)	6.73 (1.84)*	-0.85 (2.18)	0.28
(2) SOYBL	-2.2 (0.3)	0.003 (0.001)*	0.01 (0.03)	0.04 (0.07)	-0.04 (0.28)		0.05 (0.74)	3.58 (1.49)*	0.24 (1.65)	0.26
(3) COYNL	-5.8 (6.9)	0.0063 (0.0002)*	0.0006 (0.0094)	-0.054 (0.028)	0.067 (0.077)	0.03 (0.07)	0.03 (0.02)	0.05 (0.40)	0.57 (0.48)	0.98
(4) OVGTL	133.6 (58.5)*	0.006 (0.001)*	-0.03 (0.08)	-0.44 (0.22)	2.02 (0.63)*	0.10 (0.65)	0.06 (0.21)		97.73 (3.71)*	0.96
(5) NUSRL	-113.1 (300.2)	0.11 (0.02)*	1.12 (0.42)*	-0.19 (1.03)	0.35 (3.27)	-2.95 (3.26)	2.34 (1.02)*		191.51 (33.09)*	0.90
(6) FLORL	-616.4 (485.2)	0.10 (0.01)*	0.93 (0.57)	-0.30 (1.41)	-0.79 (4.37)	-6.7 (4.4)	3.03 (1.37)*		356.3 (30.8)*	0.93
(7) FRSTL	-616.4 (485.2)	0.071 (0.003)*	1.93 (0.70)*	-2.33 (1.63)	5.20 (5.34)	-1.88 (5.22)	4.77 (1.71)*		370.52 (30.71)*	0.96
(8) FCROL	520.5 (222.3)*	0.003 (0.002)	0.28 (0.32)	1.17 (0.82)	-5.61 (2.44)*	-3.26 (2.44)	-1.20 (0.77)		54.07 (14.20)*	0.35
(9) FRNTL	-90.9 (281.2)	0.061 (0.006)*	0.83 (0.43)*	0.43 (1.00)	-2.28 (3.18)	0.28 (3.09)	1.74 (0.98)		121.3 (18.02)*	0.82
(10) VEGTL	-308.7 (168.4)	0.011 (0.002)*	-0.33 (0.23)	-1.66 (0.64)*	4.92 (1.80)*	1.05 (1.85)	0.08 (0.60)		136.02 (10.69)*	0.89

accuracy of the final estimate of loss is hard to assess since there is a subjective judgment in the initial estimate of percentage leaf damage and another subjective judgment in relating leaf damage to yield loss. Surveys which have been done also lack an organized geographical grid to be assessed at uniform intervals. Observations were made randomly over a years period without standardization.

The relationship between crop yield and leaf injury induced by oxidants has not been adequately defined. There have some functions for yield vs. leaf damage produced for crops fumigated with sulfur dioxide (Hill and Thomas, 1933; Brisley and Jones, 1950; Brisley _et al_, 1959). Problems arise when these are applied because of the mixture of oxidants and SO_2 present in affected areas. Only the western regions presently have a single major pollutant (oxidant) acting without an interacting sulfur pollutant.

The surveys would be placed on a much more objective basis if crop yield-leaf damage functions were produced for the major crops even if short duration exposures were used. The application of such functions would be difficult since enormous man power requirements would be involved and the expense of implementing such a program with qualified observers would be prohibitive. The outlay necessary to effectively monitor a large production region might not be worth the assessments.

The main drawback of Oshima's oxidant crop loss models is their specificity. Ozone dose-crop yield models must be developed for each crop considered before any assessments can be made for that crop. This development is time consuming and expensive, but alternative procedures require the injection of more subjective judgment. Only one ozone dosage-crop loss function for alfalfa is presently available from this method. Therefore, the method may have good potential for the future, but the inventory of such functions must be increased in order for it to become highly useful.

The economic damage function developed by Liu and Yu (1976) for prediction of vegetation losses from air pollution appears to be a step towards the desirable goal of including more of the significant environmental variables in the damage functions. However, the method has a number of inadequacies which limit its usefulness.

Among the inadequacies are the use of pollution potential and crop loss figures from the SRI studies (Benedict _et al_, 1971, 1973). Therefore, the analysis was carried out using values obtained from a questionable data base. The pollution potential and crop loss figures are only rough estimates and can only lead to rough estimates in the analysis. Also the coefficients of some variables appear to be not significant for most of the crops tested. Other variables or shorter time summations might be more appropriate.

In spite of the limitations, estimates of vegetation loss for the 10 crops or vegetation classes may be calculated from the equations for counties where the appropriate weather and pollutant data are available. Most of the functions from Liu and Yu (1976) were derived for aggregate crop categories such as "other vegetables," "field crops," and "forestry." If one attempts to apply the model, a crop can be readily fitted into one of these categories, but in doing so one must take on the additional uncertainty involved in the assumption that all crops in the category respond in the same way to each environmental variable of the function.

One of the goals in this report is to devise a method, or methods, to incorporate weather and other environmental influences into crop production functions.

We have found essentially no data for crops in California which show weather factor-yield relationships. Such equations may have to be developed as needed from the available crop yield and weather data.

It was noted previously in this report (V, C, 3, a) that yield may be correlated with (1) direct weather data, (2) calculated soil moisture status, or (3) evapotranspiration. The regression against direct weather data would be the first choice of methods because it is the simplest whether annual or shorter time averages are use. The use of curvilinear regression seems desirable especially in an area where supraoptimal temperatures are common as in many parts of California (Thompson, 1964).

The correlation of yield with soil moisture status has been more successful than direct use of weather data under some conditions (Baier and Robertson, 1968), but it requires a prior study of soil characteristics in the area of interest and might lead to too much complexity. In addition, the bulk of California crops are grown on irrigated land and the soil moisture methods were not designed for that condition.

The use of evapotranspiration for correlation with yield might be best to consider if weather data alone are insufficient.

If multiple regression analyses of crop yield in terms of weather factors are done in an area where air pollution damage occurs, it would no doubt be advisable to include the air pollution level as one variable. This would be possible only in those areas where sufficient data on pollutant levels is available. It may be feasible to take advantage of variations in pollutant levels of different regions, as was done by Oshima et al, (1976), in order to obtain sufficient data to include pollution as a variable in the analyses.

Research studies have provided an understanding of many of the basic relationships between the most important environmental variables and the growth and yield of crop plants. It must be concluded, however, that there is almost no data base available which can be used for an objective assessment of the influence of these environmental variables on yields of a major portion of the crops and vegetation in one agricultural region such as California. There are methods available which can be, and to some extent, are being used to generate data for more objective assessments. It may be necessary or desirable to continue using the less objective models for assessments and analyses until more objective methods are available.

b. Bayesian Approach to Incorporating Prior Information in Response Functions

Throughout this section, it has been stressed that the basis of any analysis of pollution effects on agricultural production is an estimated response (or production) function with the relevent pollution indices as explanatory variables. However, a daunting range of problems in empirical field experimental results have been raised. Thus the currently available empirical results need additional information on the relationships before they can be used in a comprehensive economic model. This additional information, or prior information, may take several forms: (a) Constraints on the sign or range of coefficients to ensure "feasible" projections or resolve multicollinearity problems, (b) Prior distributions on the value of some or all parameters based on data from similar experiments, or (c) Prior distributions on the value of some or all of the parameters based on the subjective opinion of "experts" in the area.

While applied statisticians often subjectively influence the outcome of their analysis based on their theoretical expectations, the Bayesian approach makes this type of prior judgment explicit and formal as well as allowing the formal inclusion of a wider range of prior information than the traditional classical approach.

Bayes Theory. Bayes theory utilizes the definition of conditional probability to show the relation between:

Prior information on a parameter - $P(\theta)$

Information on θ -$P(y/\theta)$

The posterior distribution on θ -$P(\theta/y)$

that is $P(\theta/y) \propto P(\theta)\, P(y/\theta)$(1)

Point estimates for θ, $\hat{\theta}$ can be obtained by minimizing an appropriate loss function over the posterior distribution. For example, if the posterior is distributed normally, a quadratic loss function will lead to the same point estimate as that obtained from a classical least squares approach.

Prior Probabilities. The debate in the statistical literature over the merits of the Bayesian approach is still active, since the formal incorporation of subjective priors with data implies that probabilities based on a subjective "degree of belief" by an expert are as admirable as those based on frequency data. This is debatable in classical statistical terms, but from the perspective of a decision maker who cannot wait for the ideal experimental results, subjective information has to be used, and is thus best used in an explicit and formal statistical manner.

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(1) Where the symbol $\propto$ means "proportional to"

An empirical examination of alternative methods of obtaining priors may be found in Winkler (1967).

Operational Problems. A significant problem in implementing a Bayes approach to multiple variable response functions with n variables results from the n dimensional integration implied by the formation of the posterior distribution. This computational problem may be reduced if the prior distributions belong to a class of "natural conjugates" that may be combined analytically.

An example of the use of prior information in a Bayesian manner to estimate a production function is in Zellner and Richard (1973). A comprehensive theoretical treatment of Bayesian estimation may be found in Zellner (1971).

The review of the literature on physical factors and agricultural production functions suggests that prior information will be needed to derive meaningful relations and that the Bayesian approach is the most logical and rigorous way to incorporate it.

5. Summary

Methods of estimating crop production in relation to environmental factors were discussed with regard to problems encountered, field survey methods, and the use of statistically derived production functions.

General problems. Much research data pertaining to crop growth or crop injury is of limited uses because it is not expressed in units which are transformable to economic units. Frequently used growth measurements such as relative growth rate (g $g^{-1}day^{-1}$) and net assimilation rate (g m^{-2} day^{-1}) are almost exclusively relevant to scientific interests. In other instances there are described effects of environmental variables on growth or injury of one portion of a plant, such as leaves, which bear an unknown relationship to the marketable products of the plant which may consist of seeds or roots.

There are difficulties in determining environmental variable-yield relationships because in the field there are a number of factors influencing yield which cannot be individually controlled and in the various controlled facilities, ambient conditions cannot be duplicated.

Existing outdoor variations of environmental factors can be analyzed statistically to estimate their influences on yield responses, but here also, there are some problems. Some of these may arise because of: (1) factor interactions, (2) correlations between factors, (3) limitations in the range of variables of regression analysis, or (4) uncertainties where quantitative measurement of factors is difficult, e.g., diseases.

Field surveys. The field survey is a method which has been used for estimating crop losses resulting from air pollution. The estimates which are based on the judgment of trained observers. A state-wide survey was first made in California (Middleton and Paulus, 1956) and surveys were used later there and in other states.

Production functions. Crop yield has been related to weather variables on many occasions by functions usually derived from multiple regression analysis (Baier, 1973; Stanhill, 1973). In a few instances, regression on a single weather variable has been successful (Phipps et al, 1975; Staple and Lehane, 1954a). Most studies have related yield to direct weather data, calculated soil moisture content or evapotranspiration, or have used combined approaches. Nearly all reports have analyzed yield in areas where the water supply was by natural rainfall. Field grains are the crops most frequently studies. The reported amount of yield variation accounted for in terms of weather factors has been variable, less than 1 percent to greater than 90 percent in many cases. There is some evidence that the accuracy of the analyses is greater in regions of lower rainfall (Lewin and Lomas, 1974).

Air pollution loss functions. There is little experimental data from which objective air pollution loss functions can be made. A number of air pollution-plant damage functions have been derived from controlled environment studies in which the percentage leaf damage was recorded following a single exposure (Heck and Tingey, 1971; Heck, 1976). The relationship between leaf damage and yield is little understood, but it has been studied for some crops exposed to sulfur dioxide (Brisley et al, 1959).

A method has been developed for producing crop loss-ozone dose functions under field conditions using ambient ozone variations at different sites. The crop-dose conversion scale for alfalfa has been published (Oshima et al, 1976).

Losses of vegetation due to air pollution in the United States were estimated in a study by Stanford Research Institute (SRI) (Benedict et al, 1971). Equations to calculate losses used estimates of pollutant levels based on hydrocarbon, sulfur dioxide and fluoride emissions in the most populous areas. A crop sensitivity factor was derived from visible symptoms and other sources with a number of subjective assumptions involved. A regression analysis model was developed by Liu and Yu (1976) which uses the crop sensitivity factor and calculated pollutant levels from the SRI study, but has calculated regression coefficients for 5 meteorological variables as well. No modification of the questionable SRI data base was offered.

SECTION VI

FARM STRUCTURE, PROFITABILITY AND RISK CHANGES DUE TO AGRICULTURAL CROP YIELD CHANGES

While we recognize that not all air pollution effects in agriculture are adverse, in this and subsequent sections we are formulating a framework in which we assume that air pollution adversely affects crop yields and increases the marginal cost of production. Thus, we may expect subsequent changes in production patterns and in farm firm profitability. From a theoretical perspective the problem is one of how farmers adjust to technological external diseconomies imposed by air pollution.

In modelling this adjustment problem we are confronted with three general methodological alternatives: (A) programming models of mathematical optimization by "representative" farm and aggregated region; (B) simulation model with production function; (C) regression estimation of an aggregate farm production function or aggregate profit function. The strengths and weaknesses of each general approach will be discussed as well as specific modifications of each approach. Particular attention will be focused upon extending the models to account for risk inherent in farmers' decisions due to factors such as air pollution, weather, changes in consumer tastes, and combinations thereof.

Before proceeding, it should be understood that we are building upon yield response functions derived from previous research or estimated in Section V. What is required are sufficient functions that relate the incidence and magnitudes of air pollutants (and other physical factors, including interaction effects) to crop yields. The importance of other factors (fertilizer, water, pesticides, etc.) depends on the substitutability of physical inputs. For example, if yields are reduced by air pollution damage, farmers may respond by planting more acreage, hence increasing use of the aforementioned inputs. The estimated response functions become the basis for forming input-output coefficients(1) relating the use of each input to a unit of output of each farm activity.

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(1) This is not to be confused with input-output coefficients in "INPUT-OUTPUT" analysis, the subject of III,A. In I-O analysis, an input-output coefficient shows the amount of output from one sector required per unit output in a given using sector. (Converted to value terms, it shows the value of output from one industry required to produce a dollar's worth of product in another industry).

A. MATHEMATICAL OPTIMIZATION MODELLED BY REPRESENTATIVE FARM AND AGGREGATED REGION.

The use to which we put our matrix (array) of input-output coefficients depends upon the specific research questions we want to answer. In this section we will consider programming models which are typically comparative static and conditional normative. That is, they are usually concerned with single time periods and tell the researcher what "should be" rather than "what is" or "what will be". Extensions of the models to make them multiperiod and thus predictive will also be mentioned.

The structure of Section A will be as follows: (1) general description of linear programming (LP); (2) outline of a simple LP model of "representative" farms in Yolo county, California; (3) use of LP to derive aggregate (regional, statewide, or national) agricultural supply; (4) methods of accounting for risk in LP modles; (5) incorporating air pollution effects into programming models.

1. LP in General[2]

LP is primarily an allocation model that can solve simple to very complex problems of optimization. For example, it can solve a profit maximizing problem for the individual farmer and a welfare maximizing problem for a social system. It must have at least three quantitative components: an objective function capable of being maximized or minimized, alternate methods or processes for attaining the objective, and resource and other restrictions.

The basic LP assumptions are (1) linear production relationships (i.e., constant input-output coefficients); (2) the linear relationships are inequalities (a productive activity can use less than or equal to, but not more than, the amounts of resources available); (3) a linear objective function; (4) structural relationships must be specified (as opposed to being estimated in an econometric model); (5) additivity (total product of all activities must equal the sum of individual activities); (6) perfect divisibility of inputs and outputs; (7) finiteness (there is a limit to the number of alternative activities and resource restrictions that can be considered); (8) single-value expectations (resource supplies, I-O coefficients, prices known with certainty). Obviously, there are many real world situations for which these assumptions are too abstract. For our purposes, relaxation of assumption (8) and consequent allowance for uncertainty is the most important.

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(2) References: Heady and Candler (1964), Baumol (1965).

2. LP Model of a Farm: An Example

A good example of the use of LP in a static environment is a study by Dean and Carter (1961)(3) that attempts to determine the most profitable cropping patterns in Yolo County, California given definite assumptions as to resource availability (particularly capital and labor), institutional arrangements (land tenure system and acreage allotments), "expected" yields and prices (normal, in this study), and efficient production techniques. Given that Yolo County is a fairly homogeneous farming area(4), four typical size (or "representative") farms were selected to represent a reasonable array of alternatives. These were also defined on the basis of soil type, machinery, operating capital, and rental contracts.

Among the data requirements for this study or any other farm planning model using an LP format are prices of inputs (i.e., variable costs) and outputs, yields, fixed land and machinery costs, and per acre machinery power requirements for each crop and time period (within a season).

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(3) The basic LP model used by Dean and Carter in matrix notation:

$$\text{maximize} \quad Z = P'X$$

$$\text{subject to:} \quad A X \leq b$$

$$X \geq 0$$

Where: P is an $n \times 1$ vector of (discounted) net returns resulting from a one unit increase in the j^{th} activity.
X is an $n \times 1$ vector of activity levels.
A is an $m \times n$ matrix of input/output coefficients specifying the amount of the i^{th} resource required per unit increase in the j^{th} activity.
b is an $m \times 1$ vector of resources.
The parameters P_j, a_{ij}, b_i are considered to be constant in the general problem.

(4) Yolo County is characterized by highly commercial and highly mechanized farms. There is relatively little livestock production and among the major crops are alfalfa, barley, sugar beets, and processing tomatoes.
Gilson (1960) has applied LP to a single (but more complex) enterprise in Canada. The Gilson model develops alternative farm plans for a livestock operation based on different assumptions as to crop rotations, livestock activities and rations, given prices of inputs and outputs, and subject to resource restrictions.

Dean and Carter accounted for the possibility of pronounced yield and price variability by estimating both the income level and variability associated with each cropping pattern. This allows the research to present more and less risky alternatives to farmers.

It was not an objective of this study to obtain county-wide aggregate optimal cropping patterns, but it could be used for such a purpose by applying the results to all farms in each size category and summing across the four categories.

3. Aggregate Supply Response(5) Modelled by "Representative" Farm

Estimation of supply response is of general importance in agriculture. Projections of acreages and yields of crops are required under alternative price levels, government programs (such as acreage allotment or price support, or pertinent to this project, air pollution standards), input costs, and technology. Programming is only one approach, but offers advantages in the relative speed with which one can calculate changes in output, net returns (or any other objective), resource allocation, resource demand, or cropping pattern due to varying parameters such as air pollution standards.

Supply studies are partial equilibrium in nature, i.e., they take market demand (prices) as given. This presents problems when there are several crops competing for land. Also, the effects on consumers of alternate levels of agricultural supply as well as supply instability cannot be measured.

Noting again that programming is a normative tool, programming models of supply give optimal solutions (or what "should be"), but are generally poor predictive tools. A slightly less important problem with this approach is that of aggregation bias. That is, modelling "representative" farms to represent the supply response of groups of farms may give a solution that differs from that which might be obtained by modelling every farm separately. Nevertheless, there are methods of minimizing aggregation bias. Day (1963a) proposed three sufficient conditions for unbiased aggregation (for references on notation see footnote (2)): (1) identical input-output matrics (the A matrix); (2) proportional variation in the net returns vector (the P vector); (3) proportional variation in the vector of restraints (the b vector). These conditions have been subject to criticism. Miller (1966) and Lee (1966) have shown that conditions (2) and (3) are unnecessarily restrictive while Paris and Rausser (1973) have suggested a framework for dealing with nonproportionality in the net revenue and resource vectors as well as the matrices of technical coefficients. If Paris' and Rausser's suggestions are correct, the researcher can avoid the time consuming and costly collection and assembly of data for a large number of individual farms.

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(5) Overviews of agricultural supply analysis can be found in Nerlove and Bachman (1960) and King (1975).

The commonly used procedure for making programming models of supply response more predictive is that of recursive programming (RP)[6]. RP is essentially a synthesis of regular LP (thus it has a linear objective function and linear constraints) and regression analysis of time series data. The predictive capabilities of RP are due to the use of flexibility constraints which are usually estimated by regression techniques. Maximum and minimum flexibility constraints represent upper and lower bounds on allowable changes in the level of each enterprise in the programming solution from one year to another. That is, these constraints relate the production pattern of one year with that of the preceding year under the assumption that a farmers' current production decisions are deviations from the allocation pattern of the preceding year. There are many factors that may cause a farmer to be unwilling to make large changes in his established production patterns: risk and uncertainty due to demand factors, weather, other physical factors such as pollution[7], institutional restrictions (acreage allotments, for example), or simply personal preferences related to firm goals. Flexibility constraints indirectly measure the influences of these factors.

Since the predictive accuracy of RP models rests on the estimation of the flexibility constraints, there has been appropriate attention to this matter in the literature. Alternative methods of estimation have been proposed by Schaller and Dean (1965). More recently Sahi and Craddock (1974) have criticized previous studies for ignoring the effects on flexibility coefficients of year-to-year changes in specified economic and noneconomic variables. They proposed an alternative approach to incorporate such changes and found that the predictive performance of RP models was enhanced.

Before proceeding to the problem of accounting for uncertainty, the possibility of utilizing a multiperiod framework should be briefly mentioned. At the firm level, multi-period LP models (MLP) attempt to describe the

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(6) Day (1963a) is a good general reference for RP.

(7) The use of flexibility constraints with RP might be applied to the air pollution problem. For example, suppose we want to predict the consequences of alternative standards upon regional agricultural supply. Furthermore, suppose we have abatement technologies that are improving over time. Aside from the question of the costs of alternative abatement technologies (which can be modelled in a cost minimizing LP framework), we could use flexibility constraints to place bounds on allowable year to year changes in the magnitudes of particulate pollution in a given air shed.

process of firm growth by allowing intertemporal relationships with respect to consumption and investment(8). The entrepreneur is assumed to maximize the present value of a stream of net returns over some planning horizon. On an aggregate level MLP can be sued to describe an optimal time path for the development of a region (or regions) in response to variation in specific parameters. For example, Horner (1975) used an MLP model to analyze changes in the quantity of nitrogen fertilizer applications and land utilization by soil types in response to charges on drainage disposal of NO_3-N. The area under consideration was the Westlands Water District in California and the purpose of the study was to determine the economic impact of EPA water quality standards.

4. Methods of Accounting for Risk Aversion in Farmers' Decisions

Let us start with the assumption that farmers must make risky decisions that in certain areas are further complicated by the uncertain effects of air pollution on crop yields. That is, recognizing that the entrepreneur has a certain utility for risk, straight-forward profit maximizing assumptions of behavior are unrepresentative of the actual behavior of farmers(9).

Thus, there are important empirical(10) reasons to include risk aversive behavior. The inadequate treatment of risk in LP models has been a major factor accounting for the discrepancy between the actual and predicted behavior of individual entrepreneurs, and in aggregation of "representative" farms, has led to both overestimated supply responses and overspecialization in enterprise choices (i.e., in crop and livestock activities).

There are three general approaches to risk programming (Kennedy and Francisco, 1974): (1) expected gross margin/dispersion analysis (utility function continuous); (2) game theoretic approaches; (3) safety-first constraints.

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(8) Examples: nonstochastic Boehlje-White model (Boehlje, 1967); variations in crop yields allowed via Monte Carlo methods (Johnson *et al*, 1967).

(9) In fact Lin, Dean and Moore (1974) studied six large California farms and found profit maximization to be inferior to Bernoullian utility maximization and lexicographic utility maximization, respectively, in explaining the actual behavior of farmers.

(10) Theoretical considerations cannot be ignored either. The specification of farmers' objectives as maximizing utility is theoretically superior to a profit maximizing goal.

In the first approach, quadratic programming(11) (that incorporates a quadratic objective function) has been a popular technique for directly deriving the expected income-variance (E-V) frontier(12). The use of the E-V criterion is equivalent to maximization of the expected value of an exponential utility of income function if income is normally distributed (Freund, 1956). If a utility function is specified, the optimal decision is specified by the point of tangency between the E-V frontier and the highest utility locus in E-V space(13). In the absence of a utility function, the decision maker himself must select a point on the frontier. Applications of this approach include Wiens (1976) in which the impact of yield uncertainty in peasant agriculture is examined. Wiens is also concerned with the uncertainty faced by peasant farmers regarding the future impacts of new technology. Farmers in regions of heavy air pollution may be facing an analogous situation. They are confronted, in current time periods, with the adverse effects of pollution. In future time periods they are facing uncertainty regarding abatement technology and the political decisions necessary to implement such technology and enforce standards.

Hazell (1970), among others, has utilized a game theoretic approach in a risk programming framework in which the classical decision rules of game theory are applied. Basically, in this approach all competitive forces and uncertainty facing farmers are specified components of "nature". The farmer then is playing a game against nature (he can win or lose) when he decides on enterprise choices.

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(11) The basic QP model:

Minimize $x'D\,x$
subject to $A\,x \leq b$, i.e. same production system as in LP
and $f'x = \lambda$, $\overline{x} \geq 0$
where:
D = variance-covariance matrix of enterprise gross margins
f = a column vector of gross margin forecasts
λ = a scalar

By parameterizing λ a sequence of efficient E-V solutions is obtained; that is, for any gross margin E, the variance V is as small as possible.

(12) How and Hazell (1968) and Stovall (1966) have also suggested the QP approach.

(13) Hazell (1971) suggests a linear (LP) alternative to QP in deriving optimal farm plans under risk. Instead of minimizing variance for a given total gross margin, he proposes minimization of the total absolute deviation (A) of total gross margin. Thus, an E-V frontier replaces the E-V frontier. The E-V approach has advantages when there are shewed (as opposed to normally distributed) outcome distributions and when good quadratic algorithms are unavailable.

QP has several advantages over the game theory approach among which are: (1) QP can specify a series of farm plans whereas the game theoretic approach is rigid for any given decision criterion; (2) QP takes explicit consideration of the covariance relationships of gross margins; (3) QP is able to incorporate any probability distribution for state outcomes.

The third approach assumes that the probability of some critically low value or worse of expected net returns (total gross margin) is determined along with the expected value of net returns. This is usually termed a safety-first approach. Boussard (1971) and Boussard and Petit (1967) propose focus loss constrained programming (FLCP) as linear alternatives to QP. They conceive of farmers' behavior as maximizing expected income subject to a specified probability of attaining some minimum level of income. The FLCP approach is defended on the grounds that it produces farm plans similar to those actually implemented. A more general defense of this approach or any linear alternative is that LP algorithms are generally available to researchers whereas appropriate QP algorithms may be harder to obtain. Moreover, the QP approach has extensive data demands, especially the variance-covariance matrices of income.

On the other hand, the specification of the admissable loss constraints depends upon detailed and subjective local knowledge. Thus, as the level of aggregation increases, so does the cost of obtaining necessary knowledge for different localities.

Webster and Kennedy (1975) suggest a modification of the Boussard and Petit approach. The latter is actually being used in an aggregate programming model (using "representative" farms) of Australian agriculture(14). The basic modification is technical in nature: Boussard and Petit specify the minimal possible income level as a constant; Webster and Kennedy prefer the specification of indifference curves showing the trade-off between expected income and minimum level of income.

Finally, there are methods of providing solutions to sequential decision problems where net returns, input-output coefficients, and resource supplies (or any combination thereof) are all stochastic. Discrete stochastic programming has been suggested by Cocks (1968) and has been empirically applied by Rae (1971). Without going into excessive detail, the discrete model may be valuable in the specification of utility functions as objective functions and the incorporation and evaluation of new information. This method sounds appealing in the sense that new information on both the effects of air pollution on crop yields, and farmers' reactions to it, will become available over time, thus necessitating the updating of any economic model.

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(14) Kennedy and Francisco (1974) compare alternative ways of incorporating risk in "representative" farm models with the intention of accounting for risk aversion among Australian farmers in the aggregate model.

A regional model of this type could be developed based on "representative" farms, although data collection (of decision dates, subjective specification of probabilities for different states of nature in addition to normal LP data requirements) would be time consuming and expensive. Also as the number of individual "representative" farms needed to model the region grows, the dimensions of the problem become vast. For example, input-output coefficient matrices would have to be constructed for each state of nature in time period 1. Then, depending upon the actual outcome in period 1, period 2 matrices would have to be constructed that were conditional upon the outcome in period 1. This is the sequential nature of the problem.

5. Incorporating Air Pollution Effects into the Programming Model

In this section we will start with a simple example of how the effects of SO_2 on wheat might be incorporated into an LP model. Following this, we will mention the advantages of parameterizing the technical coefficients that relate pollutants to yields and the use of such parameterization to derive efficiency frontiers relating expected income to pollution levels.

Suppose that we have crop specific estimates of the effects of different types of air pollutants on yields(15) in a geographic region in which the levels of pollution are specified as high, medium, or low(16). Furthermore, the estimates are specific as to soil type. This means that other factors such as various atmospheric conditions and soil moisture content are assumed to be insignificant insofar as they interact with air pollutants. While this may not be realistic, it reduces the size of the problem.

A specific row in the A matrix (see footnote 3 for notation) appears as follows:

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(15) Or at least information on plant growth that can be converted to a yield per acre basis.

(16) Alternatively we can look at three geographic regions classified as high, medium, and low pollution regions.

$$a_{11}x_1 + a_{12}x_2 + \ldots\ldots + a_{1n}x_n \leq b^o$$

For example, if b^o is the total amount of land available for cultivation on a farm in our particular region of interest, and x_1 represents the production of one unit of wheat, then a_{11} is the input-output coefficient relating the quantity of land that is required to produce one unit of wheat. Similarly x_2 might be sugar beets and a_{12} is the amount of land required to grow one unit of sugar beets. The inequality means that the farmer cannot use more land than is available to him.

Now suppose that the farm land in question is composed of two soil types, A and B. In programming, wheat produced on type A soil, wheat produced on type B soil, sugar beets produced on type A, and so on ---- must be specified as different activities (or processes). Thus, wheat produced on soil type A with a high concentration of SO_2 would be specified as one activity or process. Each process is represented by a vector of input-output coefficients (or per unit resource requirements).

Thus, we might have six processes for wheat:

Type A soil, high SO_2 = x_1
Type A soil, medium SO_2 = x_2
Type A soil, low SO_2 = x_3
Type B soil, high SO_2 = x_4
Type B soil, medium SO_2 = x_5
Type B soil, low SO_2 = x_6

The dimensions of the problem grow rapidly, if we consider that wheat might also be adversely affected by nitric oxides (6 x 2 = 12 whest processes).

Suppose that yield response research has shown that the yields per acre of wheat on soil type A are 20, 30, and 40 bushels under conditions of high SO_2, medium SO_2 and low SO_2, respectively. Furthermore, we define high SO_2 pollution as emissions of 500 million pounds per year from all sources. Medium SO_2 pollution would be represented by 250 million pounds per year, and low would equal 75 million pounds. These figures are arbitrary. In comparison, Kohn (1971) projected approximately 1.4 billion pounds of SO_2 pollution for the St. Louis airshed in 1975.

For soil type A, part of the A matrix might appear as follows:

$$\underset{\text{(high)}}{20\,x_1} + \underset{\text{(medium)}}{30\,x_2} + \underset{\text{(low)}}{40\,x_3} \leq b_1$$

where: b_1 is the total production of wheat allowed on soil type A based upon historical records of cropping patterns, intuition, etc. Pollution concentrations might be represented as follows:

$$500\ x_1 \ + \ 250\ x_2 \ + \ 75\ x_3 \ \leq \ b_2$$

where: b_2 might be defined by some measure of SO_2 pollution potential that depends upon recent historical incidences. With our simple model we can then specify additional constraints to incure that only one pollution level could occur at a time.

Thus, for any given discrete level of pollution, optimal output and cropping mix may be obtained. Discrete changes in output and cropping patterns can then be derived so that one would have a linear approximation of an efficient production-pollution frontier.

We are not aware of the use of such an approach to air pollution-agricultural system modelling. Theoretically and empirically, it appears to be the simplest method of obtaining optimal cropping patterns for given alternative pollution regimes.

There are, however, two problems. The first is that we can only obtain a series of discrete solution points (though this may be due, in part, to tne nature of our experimental results which are likely to be discrete response surfaces). Second, in a multiple crop, multiple air pollutant, multiple soil type region, the dimensions of our model will rapidly surpass our time and computer constraints.

We may be able to partially mitigate these problems. By utilizing response functions in which we have estimated coefficients on interaction terms (for example, SO_2 with fertilizer, SO_2 with water, SO_2 with wind, etc.), we can parameterize both the level of pollution in absolute terms and the coefficients of inputs affected by pollution. This approach has advantages over the previous approach in at least two respects. It greatly reduces the dimensionality of the problem. Second, it allows more precise adjustments of cropping patterns to pollution levels, i.e., we are closer to approximating a continuous production-pollution frontier.

B. SIMULATION MODEL WITH PRODUCTION FUNCTION

Naylor et al. (1968) have defined simulation as a numerical technique for conducting experiments on a computer which involves a mathematical model describing a system. More generally, it is an approach to the study and use of models (Orcutt, 1960). It should be stressed that it is only a technique - an alternative approach to conventional mathematical analysis of economic systems. There is no theory of simulation.

Conventional mathematical techniques can be used to determine the way in which a model implicitly relates endogenous variables to initial conditions, parameters, and time paths of exogenous (given outside of the system) variables. Given the initial conditions, parameters and exogenous variables, simulation generates time paths of endogenous variables. A single solution generated by a simulation run is highly specific so that many runs are required to generate a more general solution.

In agricultural economics there are two general reasons why simulation has been appealing(1). First, agricultural economics have been problem oriented (as opposed to theoretically oriented) with an interest in providing a basis for informed decisions. Second, as agricultural economics have focused increasing attention on natural resources and the environment, community and economic development, firm and market decisions involving truly dynamic and stochastic elements, and large scale policy questions of regional or national scope, systems analysis and simulation have been increasingly applied. The study of problems encompassed by these categories typically involve unresolved theoretical considerations, or interdisciplinary theoretical problems. Simulation offers the chance to experiment with the predictive power of such models under alternative behavioral assumptions.

Simulation also presents an alternative when models are difficult to solve by analytical methods (usually because of stochastic elements and nonlinearities in functions). Simulation models can be solved numerically (and can approximate analytical solutions) to investigate the response surfaces of endogenous variables or to monitor the output of a model under alternative settings of decision (control) variables.

Finally, in terms of introductory remarks, simulation is a tool for studying dynamic systems especially. That is, the intertemporal relationships of the components of the system are one of the key features of the technique(2). Simulation is also a particularly good tool for handling complex systems with interacting stochastic and nonlinear elements, but aside from these attributes it cannot do any better than a well-conceived analytical model. Thus, where data are available and analytic-optimizing models can be constructed to model a system, the latter are preferable to simulation techniques.

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(1) Discussion follows Johnson and Rausser (1972).

1. Features of Mathematical Models of Economic Systems

Any mathematical model of an economic system consists of components (firms in a production system), variables, parameters, and functional relationships(3). Variables can be classified as exogenous, state, or endogenous.

Exogenous variables are predetermined and given from outside of the system being modelled. They are controllable or noncontrollable variables(4). In a production system firms might be able to control planting dates, purchases of inputs, and numbers of workers employed. In a complete economic system policy makers should be able to control the emissions of certain kinds of pollutants into the atmosphere. To the farm firm, however, air pollution is clearly noncontrollable. Additionally, weather is certainly the key noncontrollable variable for farmers as it affects growth rates, yields, and quantities harvested.

State variables describe the state of the system or one of its components at a certain point in time. These variables may be functions of both exogenous and endogenous variables and are particularly important in viewing the dynamics of the system (or sequential nature of a decision). For example, the state variables of a firm (cash on hand, inventory level, harvestable acres, soil moisture content) would depend on production, sales, cash on hand, etc., in previous time periods.

Endogenous variables are the dependent or output variables of the system and are generated by the interaction of the system's exogenous and state variables according to the systems operating characteristics (including functional relationships and identities). For example, a firm's net revenues, output, crop mix, etc. may be endogenous. In simulation experiments we are particularly interested in the effects of different levels of the exogenous variables on the values of endogenous variables.

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(2) Simulation models are implicitly dynamic except when one is simulating probability density functions.

(3) Descriptions generally follow Naylor (1968).

(4) And, exogenous variables can of course be stochastic or nonstochastic.

Functional relationships describe the interactions among the variables of the system. There are three types of relationships: behavioral, identities, and decision rules.

Behavioral relations must be empirically derived on the basis of statistical inference or determined from technical relationships. For example, the response function relates yield per acre to water, temperature, soil, fertilizer, and air pollutants. The probability distributions of random variables (temperature, water, air pollution) are also included in the behavioral relationships.

Identities are definitional or tautological statements. For example, profit equals total revenue minus total cost or the output of all individual producers of wheat in a region equals total regional output of wheat.

Decision rules specify the manner in which the farmer assigns values to the decision or control variables (in a regional systems model, we would have decision rules by which the EPA sets air quality standards). Decision rule values as well as other parameters (such as coefficients of the behavioral relationships) would be varied among simulation runs in order to observe their effects on the system.

2. Simulation Compared to LP

La Due and Vincent (1974) suggest specific areas of usefulness for simulation: (1) when complex decision processes are present that involve uncertainty and/or multiple goals; (2) where indivisibilities of inputs and outputs exist; (3) we are interested in sequential planning decisions; (4) nonlinear functions are involved; (5) we want to incorporate concepts of behavioral theories of the firm.

From the discussion in Section A it would appear that there are adequate methods of incorporating uncertainty into programming models. As the number of stochastic elements (deemed necessary to represent) in a problem grows, simulation would probably be better to use than LP. For example, a completely stochastic model which can be used in Monte Carlo simulation of alternatives would be cheaper to develop (in addition to being feasible to develop) than a stochastic programming model (see Section A). Both models, however, would be tremendously expensive relative to other techniques.

With respect to multiple goals, LP implies the maximization of a single goal with additional goals having to be represented by constraints (for example, focus-loss constraints), assuming that they are linearly related. Simulation, on the other hand, is valuable in comapring outcomes under alternative decision rules - each incorporating different sets of goals. Note again that simulation cannot generate optimal outcomes.

Indivisibilities of inputs and outputs can be handled by simulation models and also by interger programming with LP(5).

Simulation can handle sequential planning decisions, but in programming there is still recourse to recursive programming for short-run optimization or dynamic LP for long-run optimization. However, simulation does provide an advantage in that it traces out the time paths of the endogenous variables, not just optimum points over time.

Simulation models can incorporate any number of continuous or discontinuous linear or nonlinear functions, qualitative variables, and conditional relationships in any combination. In LP we must assume that linear approximations suffice to represent nonlinear functions. In QP we can use quadratic objective functions.

Finally, for our air pollution problem it is not relevant to consider outcomes generated under alternative behavioral theories of the firm.

3. Applications

Johnson and Rausser (1972) thoroughly review the use of simulation models in agricultural economics. They classify simulation models of the firm as to whether they are process, farm planning, or growth models. Within each category most of the models are stochastic, dynamic, and involve some nonlinearities.

Process models objective functions such as minimizing costs, maximizing returns over costs, and maximizing E-V utility. They involve certain types of producing and marketing activities over which the firm has control. An example is the Glickstein et al. (1962) model of a cheese plant.

Planning models usually incorporate numerous production activities with many strategies for combining them. Some contain innovative methods of handing risk. Examples include Eidman et al. (1967) and Halter and Dean (1965) compare alternative price expectation models in a range-feed lot operation.

Firm growth studies are similar to those mentioned in (A) except that they use simulation techniques or a combination of techniques. Patrick and Eisgruber (1968) formulate a simulation model to trace the time path of firm growth. Armstrong et al. (1970) combine simulation with LP while Chien and Bradford (1976) use a MLP, RP, and simulation combined approach.

We will provide a more in-depth description of three models: one that simulates an integrated physical (hydrologic) - economic system; a dynamic firm growth model; and a micro-macro model in which optimal decision rules are derived for administration of the Federal Feed Grain Program.

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(5) See Chou and Heady (1961) for applications of integer programming.

Horner and English (1976) sequentially link an LP and hydrologic model in order to simulate the agricultural production and environmental adjustments that would occur as results of environmental policies. Specifically the objective of the study is to analyze the impacts of two alternative policies of increasing the quality of irrigation return flows. The policies (increasing the price of surface water or requiring certain water use standards)(6) are two of those conceivable under the Federal Water Pollution Control Act Amendments of 1972.

The LP model derives optimal cropping patterns, optimal use of ground and project water and fertilizer for 40 subregions in a 700,000 acre area in the San Joaquin Valley. The objective function maximizes returns to land and management in the area subject to the usual physical, institutional, and market restrictions including the total amount of surface water available and crop rotation requirements.

The results of the LP model function as inputs to physical submodels that analyze the hydrology, salinity balances, and nitrogen concentrations. In the submodels, the effects are estimated of irrigation water and fertilizer use on water table depths and the quantity and quality of irrigation return flows. Costs of collection and disposal of return flows, and employing tile drainage systems are calculated. Then production costs are adjusted accordingly in the LP model for the following year. Solutions from the models are derived on an annual basis and are iterated until they simulate the adjustments due to water-use changes that result from alternative policies.

The models were used to project future crop acreage, nitrogen fertilizer use, water use, and net returns to land and management under "no policy", the pricing policy, and management policy alternatives.

This particular approach to evaluating alternative policies is limited in one main respect: it is only a crude approximation of the hydrologic-economic system in the study area. Among the limiting assumptions are that current irrigation practices and the chemical composition of available water will hold in the future. Both are likely to change which suggests that the single period optimal LP solution is also unlikely to be representative of future time periods.

In the Horner-English model, pollution producing and pollution receiving firms are both in the agricultural sector. An analogous approach to the air pollution problem would be much larger in scope since air pollution externalities are produced by nonagricultural firms and individuals' autos, whereas the recipients of the pollutants are in agriculture (excluding the major sufferers of pollutants - individuals in all sectors).

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(6) Both policies are designed to improve the efficiency of water use: (1) the increased price is an alternative to an effluent charge; (2) requiring certain management practices in water use is expected to improve efficiency by 30 percent.

Chien and Bradford (1976) integrate multiperiod LP (MLP) and simulation techniques into a recursive sequential model of the farm firm growth process. Applying the model to a beef enterprise, they are able to compare alternative management strategies and how they affect alternative growth processes. In considering the problem of air pollution effects at some level of aggregation, a model of farm firm growth does not have specific relevance. However, the techniques have relevance in that policy makers might want to compare alternative abatement strategies in the nonfarm sector (the source of air pollution) and then explain and predict alternative time paths of regional growth processes. In other words, if air pollution is reduced there are going to be abatement costs in the nonfarm sector and presumed benefits in the farm sector. The adjustments of the two sectors taken together will certainly alter existing development trends.

Basically Chien and Bradford combine MLP, recursive LP (RLP), and simulation techniques into a single sequential model. The authors wanted the optimizing features of MLP, the behavioral (flexibility) constraints of RLP, and the ability of simulation techniques to handle multiple goals, indivisibilities, and sequential decisions(7).

Phase 1 of the model consists of a Nerlovian (Nerlove, 1958) submodel that quantifies the farmer's price and yield expectations in accordance with his objectives, resources, finances, and organization. This submodel forms the basis of the MLP submodel employed in phase 2. The MLP submodel is used to derive the farmer's approximate long run plan and provide an optimal "first move". The current farm plan (from MLP), plus prices of inputs and outputs, consumption expenditures, inventories, other data and a stochastic price and yield generating scheme are inputs into the simulation model.

The simulation model then executes alternative decision-operation processes for the current plan. Since in reality the farmer probably cannot carry out the optimal plan as specified in the MLP submodel (due to uncertainty, lumpiness of inputs), flexibility constraints are constructed to place boundaries on enterprise levels in each period. Thus, a modified current plan is obtained.

Given the modified optimal current farm plan, the simulator then implements operation of the plan and executes a number of decisions regarding purchases of inputs, purchases or rentals of capital assets, borrowing, paying off debts, and depreciation of assets.

Growth of the firm was measured according to the time paths of three variables: total assets, net worth, and size of the enterprise. The simulated values were relatively close to the actual values of the variables, the differences being attributed to difficulties in accounting for household consumption and the debt repayment schedule. The model was also used to examine the effects of alternative management strategies upon growth patterns for future periods.

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(7) Remember that all of these things can also be handled without simulation techniques.

While the integrated model did incorporate dynamic and stochastic features of the growth process, it also required substantial amounts of time and money for data collection and computer software and hardware.

Shechter and Heady (1970) use a simulation model to derive response surfaces in the Feed Grain Program. The components of the model are micro units (firms) and macro units (aggregate regional outputs and the government). Allocation and production decisions for the firms (for which behavioral relationships are specified) are derived in the micro-simulator. Outputs of individual farms are aggregated and enter the aggregated market system (plus government), i. e., the macrosimulator. The decision variables (the alternative effects of which are examined in different simulation runs) are minimum acreage diversion, price supports, payment and loan rates, and diversion payment rate. The response variables are net farm revenue of participants, stock accumulation, and total treasury costs.

The main emphasis in the study is the derivation of efficient decision rules via response surface analysis. In the context of a multi-response surface a locus of efficient decision rules is provided. This is important in the respect that for any government decision there are going to be trade-offs: in this case, increasing farm income conflicts with the goal of reducing government cost.

C. ECONOMETRIC MODELLING OF THE PRODUCTION SYSTEM

A broad definition of econometrics is that it encompasses "every application of mathematics or of statistical methods to the study of economic phenomena" (Malinvaud, 1966). Malinvaud defines econometrics in a narrower perspective as the use of numerical data to test the postulated relationships of economics.

In this section we are interested in agricultural production at either the firm, industry, or regional/national level and econometric analysis of either single equation production functions or simultaneous systems. For our purposes, the latter could be production systems, biological/behavioral systems, or market systems in which supply and demand simultaneously interact. To be more specific, we are focusing on positive relationships, i.e., what is the relationship between air pollution and yield? How does it affect output and profits? In the previous section, LP gave us "normative" answers, e.e., what should the optimal cropping mix be given air pollution externalities and additional behavioral assumptions?

Within the general category of supply response[1] (see section VI, A) econometric analysis can be applied to the derivation of supply functions from data relating to production functions and individual behavior, or aggregate supply functions can be estimated directly with time-series and/or cross-section data. In the following two sections on the single equation approach to estimating biological and "whole farm" production functions, we are concerned with the positive impact of air pollution as derived explicitly from production functions. In our later consideration of simultaneous systems we are interested in the effects of air pollution on the endogenous variables (determined simultaneously within the system) in either production or market systems.

The basis of our analysis is an implicit production function,

$$f(y_1, \ldots\ldots, y_n; x_1, \ldots\ldots, x_m) = 0$$

that relates all outputs (y's) to all variable inputs (x's). Air pollution can conceptually be regarded as a variable input. If we are interested in any one output, it can be expressed as an explicit function

$$y_0 = g(x_1, \ldots\ldots, x_n)$$

Given production functions for the firm of either form, plus information on the functional forms, we can derive functions expressing outputs, costs, and derived demands for inputs in terms of prices of inputs and outputs. For example, we can derive short or long-run cost functions, the marginal products of inputs (labor, capital, fertilizer, etc.), the marginal rates of substitution between inputs, or the demand function for

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(1) As in section VI, A., Nerlove and Bachman (1960) and King (1975) are basic review articles for agricultural supply analysis.

labor. Before proceeding to a discussion of "whole farm" (aggregates of firms) production functions, we will briefly digress by looking at the biological (or firm) production function.

1. Biological Production Functions - Single Equation(2).

A typical biological production function for wheat might appear as follows (a function for sugar beets would be specified analogously):

$$Y_W = f(\underbrace{N,\ P_2O_5/K_2O}_{(a)},\ \underbrace{\text{Labor, Management, Weather, Air Pollution}}_{(b)}\ /\ \underbrace{\text{weather}}_{(c)})$$

Variables in set (a) may be varied in experiments. Hopefully, air pollution can be in (a) if there are enough observations (cross-sectional) in areas with different air pollution levels. Otherwise, it might be incorporated in set (b), variables which are fixed by the investigator. Set (c) is composed of random variables.

One firm could be represented by several of these partial production functions - depending upon the number of crops grown. Given output (final product) and input prices (factor prices), the behavioral criterion of profit maximization can be applied to a hypothetical two crop, wheat-sugar beet farm firm:

$$\max = \overbrace{(P_W A_W Y_W + P_{SB} A_{SB} Y_{SB})}^{\text{total revenue}} - \overbrace{(P_N N + P_L L + \ .\ .\ .\ .\ .\ )}^{\text{factor costs}}$$

where: P_W = price of wheat,
A_W = acreas planted in wheat,
Y_W = yield per acre of wheat,
P_N = price of N,
L = man-hours of hired labor.
P_{SB} = price of sugar beet,
A_{SB} = acres planted in sugar beet,
Y_{SB} = yield per acre of sugar beet,
P_L = wage rate,

Profit maximization is subject ot the following constraints:

$$\text{identities} \left\{ \begin{array}{l} N = N_W + N_{SB}, \text{ i.e., total N applied equals the sum of that applied to wheat and sugar beets.} \\ \vdots \end{array} \right.$$

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(2) By single equation we mean that production functions are specified as unilateral causal relationships in which output is a function of predetermined input variables. Furthermore, output is assumed to be produced independently of all other outputs and the estimated error term is assumed to be independently distributed. Typically a single equation production function at any level of aggregation would be linear or intrinsically linear in which case classical linear regression techniques could be applied.

$$\text{production functions} \longrightarrow \begin{cases} Y_W = f(\qquad\qquad) \\ Y_{SB} = f(\qquad\qquad) \end{cases}$$

The profit maximization problem could be solved using calculus with Lagrangean terms for restrictions. Additional restrictions could be added for particularly limiting factors of production. However, in reality the researcher is usually not able to derive continuous functions for each process. Also, the solution procedure becomes cumbersome as the number of crops and restrictions grows. Thus the best use of such estimated functions is as inputs to LP models.

For specialized problems biological functions may be of use, especially when we consider the time dimension (response efficiency over time, internal rate of return) and uncertainly. For example, De Janvry (1972) used corn and wheat fertilizer response data to determine conditions under which fertilizer use would be economical in Argentina (where most farms do not use fertilizer). He attempts to assess the risk attached to different dosage levels and obtains internal rates of return for particular investments in fertilizer. From a policy point of view he obtained an estimate of the social returns from alternative fertilizer price policies.

2. "Whole Farm" Production Functions - Single Equation

In this section we are specifically speaking of aggregates of firm production functions. Our starting point might be the following relationship:

$$\text{Output} = f(\text{labor, land, machinery, variable expenses, management, air pollution (say } SO_2\text{)})$$

If we are concerned with one crop, output is an aggregate of all firm outputs of that crop. If we are concerned with more than one crop the dependent variable would be product value at constant prices. Inputs would of course be aggregates also(3). The function is usually fitted to cross section data, or sometimes, cross section and time series data combined.

Among the applications of such models are analysis of supply response (see VI, A for policy questions that are pertinent) based on aggregation of firm marginal cost functions. Or, once we derive the marginal productivities of factors, they can be compared: among different regions, or with actual marginal products within the same region. For example, one might estimate the marginal product of labor and compare it to average wage rates (the two are equal at equilibrium in accordance with economic theory) in a region. In any case, once marginal products are estimated, policies can be recommended. For example, if the marginal product of labor was greater than actual wage rates it suggests that workers are being underpaid.

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(3) Two general rules for input aggregation (particularly when using the Cobb-Douglas function) are (1) the inputs within each category should be as nearly perfect substitutes or perfect complements as possible; (2) relative to each other, the categories should be neither perfect substitutes nor perfect complements.

Generally speaking whole farm functions may be useful as a positive diagnostic tool in policy analyses concerned with serious disequilibria. For example, the policy question of labor migration might be examined from the point of view that surplus labor in one region is depressing the returns to labor (i.e., causing poverty). Meanwhile a shortage of labor in another region is depressing farm returns (thereby hindering firm expansion and raising consumer prices) by causing farmers to plant non-labor intensive crops. A policy of inducing migration from the labor surplus to the labor deficit area is implied.

For purposes of analyzing the effects of air pollution in a market system where we are interested in producer, consumer, aggregate welfare effects and associated policy implications, we might view aggregate regional production functions (by crop) as inputs into a general equilibrium model. Such models are capable of being solved with LP or QP techniques and will be discussed under VII, B.

Problems in Production Function Analysis

The problems pointed out below pertain to production functions aggregated at any level.

We will briefly examine the following problem areas: (1) algebraic form, (2) simultaneous equation bias, (3) specification bias, (4) measurement problems, (5) combining time series and cross section data, (6) technological change.

Algebraic form. Whole farm functions have frequently been estimated as polynomials because the data suggests response surfaces of this type. The commonly used Cobb-Douglas function is simply a log transformation of a first degree polynomial.

The Cobb-Douglas function requires a constant elasticity of production, constant returns to scale throughout the region of production, and an elasticity of substitution equal to one. There are many alternatives to these restricting assumptions and many alternative algebraic forms. For example, Arrow *et al*. (1961) suggested the CES function in which the elasticity of substitution (between capital and labor in a two factor work) was constant, but not equal to one. With respect ot constant returns to scale, Ulveling and Fletcher (1970) estimate a Cobb-Douglas function with variable returns to scale.

Simultaneous equation bias. The question of simultaneous equation bias arises because single equation estimation procedures normally lead to biased[4] estimators when the true system is better represented by a system of simultaneous equations[5]. Most production function research has utilized the single equation approach because of computational simplicity and because it allows for theoretically satisfactory predictions of output. Nevertheless knowledge of the underlying economic structure remains unknown. Hoch (1958) found that in production functions where simultaneous equation bias exists there was a general tendency for the least squares estimated sum of elasticities to equal one (implying constant returns to scale) even though the true sum was not equal to one (implying either decreasing (sum < 1) or increasing (sum > 1) returns to scale).

Specification bias. It is not possible to completely specify and fit the true production function relevant to a given process. Usually the true functional form and complete range of input variables are unknown. Even when variables are known it may be too costly or too difficult to measure them. Thus there are specification errors in the typical function which in turn results in specification bias in the estimated coefficients.

Typical specification errors made in Cobb-Douglas studies are: (1) omission of variables (for example, neither technology in time series studies, nor management effects in cross-section studies can be explicitly measured; or, if ozone concentration really decreases alfalfa yield by 15 percent, it would be important not to omit ozone as an independent variable); (2) aggregation within inputs (no matter how carefully we define input categories there are likely to be quality differences in inputs; for example, one unit of labor is not likely to be the same as any other unit); (3) aggregation over inputs (specification bias will result if the rules in footnote (3) are violated).

Griliches (1957) obtained some general results from specification errors in Cobb-Douglas production function estimation. If an input is excluded that varies less than proportionately with the included inputs (and vice versa), returns to scale will be underestimated. The omission of a managerial input variable biases the estimate of returns to scale downwards and the elasticity of output with respect to capital upward. The omission of quality differences in labor (due to education, for example) results in an upward bias in the estimated elasticity of capital, and a downward bias in elasticity of labor and returns to scale.

Measurement problems. We have touched upon conditions for aggregation of inputs and the biases that result from aggregation bias. In this section we will deal more explicitly with actual measurement problems in variables.

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(4) Specifically, simultaneous equation bias occurs when disturbances in the production relation affect the observed values of all variables (not just the dependent variable), thus producing inconsistent estimates.

(5) See later sections for more discussion of the simultaneous approach.

(i) Output: If we have a single product, we can aggregate output in physical terms. Since most farms produce more than one crop we are typically faced with the aggregation of multi-product firms. It might be preferable to estimate aggregate functions for each crop (with the restrictive assumption that there are no interdependencies among crop choices) so that something can be said about investment in individual enterprise choices, but frequently individual enterprise data relating quantity of each input to quantity of each output are unavailable. This is especially true for cross section studies where a wide range of farms should be included. Thus, the researcher usually turns to an aggregate measure of value output. For example, if we have multiple products produced in constant proportions we can use prices as weights to obtain a value index. However, if we have multiple products in varying proportions it would be reasonable to use a simultaneous approach.

(ii) Labor: Usually, the researcher aggregates operator, family, and hired labor using wage rates as weights. But, there are problems in the following areas: what is the proper wage rate for the operator's labor? (or family labor?). Also, data are usually lacking for labor used so labor available is measured. Finally how do we account for differences in labor quality as influenced by age, education, etc. Griliches (1963) incorporated separate variables for labor and education in his aggregate agricultural sector production function. Since there was no significant difference between the coefficients, he later included labor and education as an interaction term so that labor could qualitatively improve over time (Griliches, 1964).

(iii) Capital: As Heady and Dillon (1961) suggest: a finding (based upon farm sample estimates) that capital inputs have a marginal return of so many dollars tells nothing about the productivity of different forms of capital inputs except for the sample firms. Thus, capital inputs must be categorized (again following the rules in foot not (3)). Among the factors to be considered in specifying a production function, in addition to land, labor, pollution, etc., are improvements, liquid assets, cash operating expenses, maintenance and depreciation of fixed assets. Which factors to include as capital inputs depends on the production process being examined. For example, purchased feed, seed, and fertilizer might be very important in some operations. Durables are usually very important and can be measured by the maintenance and depreciation costs (plus the rate of interest on the investment) associated with the use (as opposed to measuring their value on an inventory basis). Thus, the service flow is measured.

(iv) Land: The basic problem in measuring land is that of quality. One could use price (or cash rent) to obtain the value, or land taxes. The latter would present problems if the region were significantly urbanized. Alternatively, a service flow concept analogous to that in the measurement of capital could be employed. Land would be specified as real estate (land, buildings, equipment tied to land) and would be measured by depreciation on buildings and equipment, maintenance on buildings and equipment, plus interest on the investment(6).

(v) Management: This is probably the most difficult variable to measure in "whole farm" studies. Obviously, management ability will vary among entrepreneurs and the consequences of omitting this variable were mentioned in the section on specification bias. But what are our choices?

Management is usually considered to be part of the error term and not specified at all. In this case the residuals between production levels estimated from the fitted function and actual observed production levels are attributed to management. Alternatively, one could measure management with objective or subjective test scores. This approach has not been widely used, but Heady and Dillon (1961) used a management index and found that increasing returns to scale (as opposed to constant) "seemed" to be due to management. Doll (1974) has suggested representing management efficiency by attaching efficiency level coefficients to each input as well as specifying an overall general efficiency level(7).

(vi) Time series - Cross section data combined: Another way of handling the management effect is by analysis of covariance (ANOC) using time series and cross section data. Hoch (1962) initially introduced a constant term to a Cobb-Douglas function to represent differences in tehcnical efficiency among farms. Realizing that simultaneous equation bias would occur if either cross-section or time series data were used alone, he added a time constant to represent changes in technical efficiency over time and suggested analysis of combined time series and cross section data. Among Hoch's conclusions were that the firm effect could represent technical efficiency or alternatively, entrepreneurial capacity (management). The time effect measured weather differences (the significance of the time effect indicates that explicit consideration of weather would be useful) and changes in productivity overtime.

Paris and Hoch (1966) advocate the use of the ANOC model to allow production elasticities to vary among firms and years. Normally in production function analysis all farms are assumed to be operating with the

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(6) We are likely to have a multicollinearity problem (that is, linear dependence of explanatory variables - see Theil, 1971) in the specification of land and air pollution as independent variables. That is, urban encroachment (if our region of interest is extensively urbanized) is positively related to both land values and air pollution which is to say that the effects of urban encroachment on land values and pollution on production are collinear.

(7) C-D function to be fitted to cross section data:

$$Y_i = B_0 X_{i1}^{B_1} X_{i2}^{B_2} \text{ ecp } (\varepsilon_i)$$

With added symbols m_i to represent level of management on ith farm:

$$Y_i = B_0 M_i X_{i1}^{B_1 + m_{i1}} X_{i2}^{B_2 + m_{i2}} \exp (\varepsilon_1)$$

same function. Attempts to avoid this problem by estimating individual farm functions have generally been poor. Thus the Paris-Hoch approach includes firm and time effects both as constant terms and as components of input coefficients. The results of this approach include meaningful estimates of firm elasticities (as well as some measure of management) which makes the results much more applicable to individual farm decisions(8).

(vii) Technological change: We have just seen that the inclusion of firm and time effects in an ANOC model estimated with time series and cross-section data provides indicators of technological change. Generally, the problem of measuring technological change has arisen because of observed shifts in firm production surfaces over time. These shifts may be due to the use of new inputs (i.e., replacing old) or due to qualitative improvements in inputs (for example, labor improved due to education). From a cross-sectional viewpoint we may observe firms operating with different arrays of inputs (i.e., old and new arrays).

With time series data, a time trend variable t can be added as an independent variable to allow for technological change(9). In the case of neutral technological change (i.e., not biased toward capital or labor), t would be incorporated as a shift variable (see Solow, 1957).

3. Simultaneous Systems

In the previous section we mentioned the implications of simultaneous equation bias in production function analysis: that is, the consequences of specifying and estimating a unilateral causal relationship when in fact a system of mutually determined relationships exists. In other words, the production relation may well be embedded in a system of equations in which inputs, outputs, and other variables are mutually determined(10).

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(8) Hoch has come out with two recent articles (1976a and 1976b) on this subject. Suffice it to say that there is some disagreement over the applicability of elasticity estimates to the firm level.

(9) In a Cobb-Douglas framework, technological change can be expressed by shift variable (change in intercept) and/or by changes in the partial elasticities of production.

(10) Except where relevant, we will not discussing estimating procedures and other statistical problems. Generally, some of the problems involved in estimating a structural system are similar to those in single equation models. That is, there are similar problems in choice of variables, algebraic form of the functions, validity of assumptions and interpretation of results. Among the references for simultaneous equation techniques (and single equation) are: Foote (1955), Goldberger (1964), Malinvaud (1966), and Theil (1971).

The variables in a simultaneous system can be divided into the following categories:

(1) Endogenous: variables whose current values are determined simultaneously in the system (note that in the single equation models discussed earlier there was one endogenous variable - the dependent variable).

(2) Predetermined: current values are treated as given.
  (a) exogenous: values determined outside of the system.
  (b) lagged endogenous.

The structural model may be written in matrix form as:

$$B\,Y_t + \Gamma_1\,Y_{(t-1)} + \Gamma_2\,X_t = U_t \qquad (1)$$

where: B = matrix of coefficients of current endogenous variables (G x G in system of G structural relations)
Y_t = vector of current endogenous variables
Γ_1 = matrix of coefficients of lagged endogenous variables
Y_{t-1} = vector of lagged endogenous variables
Γ_2 = matrix of coefficients of current exogenous variables
X_t = vector of exogenous variables
U_t = vector of disturbance terms

In contrast to the structural form of the system the reduced form of a complete (the number of endogenous variables equals the number of equations) system expresses each endogenous variable as functions of only predetermined variables and disturbances. That is, each equation has only one endogenous variable and it is the dependent variable.

The reduced form of equation (1) is:

$$Y_t = \Pi_1\,Y_{(t-1)} + \Pi_2\,X_t + V_t \qquad (2)$$

where: Π_1 = matrix of reduced form coefficients of lagged endogenous variables.
Π_2 = matrix of reduced form coefficients of exogenous variables.
V_t = vector of reduced form disturbances.

and $\Pi_1 = -\,B^{-1}\Gamma_1, \quad \Pi_2 = -\,B^{-1}\Gamma_2, \quad V_t = B^{-1}U_t$

The estimation of structural coefficients in (1) provides knowledge of the underlying economic structure under consideration. The reduced form is useful for prediction, that is, predicting the impact of a change in an exogenous variable the endogenous variables(11). The reduced form coefficients Π_1 and Π_2 in (2) are referred to as *impact multipliers* and specifically "show the effect of a unit change in any given exogenous variable on the expected value of a contemporaneous endogenous variable after all the simultaneous effects of the system have been worked through" (Sarhan *et al*., 1976).

The implications for analyzing pollution effects should be apparent. Suppose that we have a market structure for crops adversely affected by air polluiton. On the supply side we might have yield equations which enable us to quantify the direct effects of air pollutants on yields. We also might have production functions (from which supply functions can be derived) embedded in the supply system. On the demand side we have the price-demand structure representing the consumer and faced by the farmer. Air pollution is obviously exogenous to this system. Aside from estimating the coefficients of the structure in which air pollutants operate, we will be particularly interested in the impacts of changing air pollution levels (they may increase in the absence of standards or decrease with the implementation of standards) on the endogenous variables in our system: yields, output, demand for inputs, profits, consumer prices, etc. We will also be interested in the distributional impact on producers' and consumers' surplus. The effects of *sustained* changes in air pollution are even more important in which case we can obtain dynamic multipliers.

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(11) The relationship between the structural and reduced forms of the model is known in econometric terms as the *problem of identification*. There are rank and order conditions for exact identification (see Theil, 1971; Malinvaud, 1966; Goldberger, 1964), but instead of citing these in econometric terms we offer a verbal description.

If two or more theories are observationally equivalent, then they have the same implications about observable phenomena under all circumstances. If we attempt to estimate the parameters of the theories, there would be no way to distinguish the parameter estimates of one theory from the other. On the other hand if we assume we have knowledge of the population distributions of the variables, and if this knowledge allows us to *uniquely* determine the value of a parameter, then that parameter is identified.

Reduced form parameters are always identified, i.e., they are uniquely deducible from the parameters of the joint distribution of the observations. The structure of the structural form is identifiable if and only if no other structure has the same reduced form. or, in other words, a structural parameter is identified if and only if it can be uniquely deduced from the reduced form parameters.

Applications of the Simultaneous Equation Approach

In this section we describe three studies that employ a simultaneous equation approach to answer alternative research questions. First, we describe the work of Lau and Yotopoulos (1972) in which they jointly estimate profit and labor demand functions for Indian agriculture. Second, we examine a biologic/behavioral model of a mosquito abatement district. Finally, we outline a dynamic econometric model of the market structure for white dry edible beans.

The analysis of an aggregate profit function is advanced as an alternative to the analysis of production. Under the assumptions that (a) firms follow the decision rule of maximizing profits, (b) firms are price takers in output and input markets, and (c) the production function is concave in the variable inputs, "there exists a one-to-one correspondence between the set of concave production functions and the set of convex profit functions" (p. 11). Among the advantages of working with a (unit-output-price) profit function instead of the typical production function are that the aggregate supply function and factor demand functions can be derived without the explicit specification of the production function(12). Furthermore, the profit function, supply function, and factor demand functions so derived may be written as explicit functions of variables normally considered to be determined exogenously to the firm's behavior. Direct estimation of these functions in the reduced form thus avoids the problem of simultaneous equation bias.

In production function analysis with labor as a variable factor, the farmer's decision variables would be output and labor input. These variables would be jointly dependent with the prices of output, wage rate, and quantities of capital and land specified as predetermined variables. However, the specification of a profit function leads to use of profits and total labor costs as jointly dependent variables. Because the right hand side of the two equations includes only predetermined variables the application of ordinary least squares (a single equation technique) will be consistent, but inefficient because of the appearance of Π_1^* in each equation(13). Thus, the authors jointly estimate the equations with Aitken's generalized least squares(14) and in fact obtain the best results by adding two constraints: $\alpha_1^* = \alpha_1^*$ and $\beta_1^* + \beta_2^* = 1$. The latter constraint spefifies constant returns to scale.

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(12) In this particular study, with labor as the variable factor and capital and land fixed, the particular estimates of importance are the labor demand and output supply elasticities with respect to wage rate, price of output, and quantities of capital and land. Also, the coefficients of the production function (Cobb-Douglas) are obtained and the hypothesis of constant returns to scale is tested.

The reduced form elasticity of a change in output with respect to a change in the quantity of land is derived because of its policy implications. For example, an increase in land will lead to an upward shift in the marginal product of labor (hence, wage rate). This reduced form elasticity, derived from output expressed in terms of the profit function, has distinct advantages over the analogous production function elasticity (of output with respect to land). In the latter, the effects of an exogenous increase in land on output can be measured, but holding other factors constant. In the profit function, other factors can be influenced by the exogenous change in land.

Sarhan et al. (1976) use a simultaneous equation approach to model a biologic/behavior system, specifically, a mosquito abatement district. The objectives of the study are to first formulate an empirical model (simultaneous system) of an abatement district in which mosquito population variables, mosquito control methods, and control method effectiveness are simultaneously determined. Second, unit cost data were applied to the endogenous variable coefficients in the model in order to compare the economic efficiency of alternative control methods(15). Third, given that

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(13) Without going through the mechanics, this is true both theoretically and empirically. The final empirical model is:

$$(1)\ \ln \Pi^{*'} = \alpha_0 + \underset{i}{\Sigma}{}_i^{*} D_i + \alpha_1^{*} \ln w' + \beta_1^{*} \ln K + \beta_2^{*} \ln T$$

$$(2)\ -\frac{w'L}{\Pi^{*'}} = \alpha_1^{*}$$

where: $\Pi^{*'}$ = profit per farm
w' = money wage rate per day
D_i = regional dummy variables
L = labor in days per year per farm
K = interest on fixed capital per farm
T = cultivatable/and in acres per farm

(14) Zellner (1962) proposes this approach to estimating a system of equations because of efficiency gains and minimization of aggregation bias.

(15) The indirect effects of changes in the stock of past sumps, ponds, etc. (or any other control method), on the light-trap index variables were calculated from the reduced form of the model. The coefficients of the exogenous variables in the reduced form are impact multipliers.

Of more interest, however, are the dynamic multipliers, i.e., the effects of unit changes in exogenous variables sustained for a period a comparison of the physical efficiency versus economic efficiency of control methods showed that the abatement district managers were making suboptimal decisions (i.e., the application of pesticides was expensive and not as efficient as other methods given the build-up in pesticide resistance), an LP model is constructed that selects the minimum cost combination of control methods subject to appropriate physical, labor, and institutional constraints. The model also assures that the mosquito population will not exceed a specified level.

Among the direct policy implications of the study were that over-reliance on chemical pesticides in the short-run would lead to more expensive physical control methods in the future, given tolerance build-up and the decreasing probability that replacement pesticides can be developed.

Vandenborre (1968) formulated a dynamic econometric model of the market structure (i.e., it contained empirically estimated demand and supply relationships) for white dry edible beans in order to (1) evaluate the impact of government price support programs, (2) study the impacts of changes in exogenous variables on the system, and (3) estimate the effects of establishing support prices above free market prices.

The supply (or production) system contained a relationship for each of four bean varieties. The relationships involved one acreage equation (since acreage data was generally unavailable) and three equations specifying production in terms of thousands of hundred-weights. Pre-determined variables included lagged prices (own and competing crop prices) and time trends(16) to indicate yield fluctuations. Vandenborre justifies this specification on the grounds that acreage data were unavailable for all varieties. However, even this line of reasoning is insufficient to justify

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(15) continued:
of time on the endogenous variables. For example, the direct and indirect effects of sumps, ponds, etc., constructed was compared to the number of locations treated with pesticides over a time horizon of eight years. Both methods were found to be beneficial in the short-run, but in the long-run the indirect costs of pesticide use greatly outweighed the short-term benefits due to tolerance build-up.

(16) The use of time trends or lagged production in supply equations can account for yield fluctuations due to externalities such as air pollution. Time trend variables also serve as proxies for many other effects (weather, technology, management improvement), thus their interpretation is difficult.

the lack of use of more satisfactory alternative specifications(17).

On the other hand, since the components of the price-demand structure are determined simultaneously, a system of eight structural equations was postulated. Structural coefficients were estimated by two-stage least squares.

The supply and price-demand structures are integrated into one dynamic model through various operations including the computation of the reduced form of the price-demand structure. Just as in the Sarhan _et al_. study, dynamic impact multipliers are obtained. With respect to the structure of the market for white dry beans the impacts of changes in the following exogenous variables were deemed to be important: price of corn (because corn competes with navy beans for acreage), disposable income (its impact on quantities supplied and demanded and on prices in the absence of government programs), and income from feedgrains.

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(17) A more satisfactory approach would have been to use an adaptive expectations or partial adjustment model on the supply side. The former has been used extensively in the analysis of agricultural supply and is expressed generally as:

$$Y_t = A_0 + A_1 \theta \sum_{k=0}^{\infty} (1-\theta)^k Z_{t-k-1} + \varepsilon$$

where Y_t = vector for which explanation is sought (supply or acreage)
Z_t = vector of explanatory variables
A_0 = parameter vector
A_1 = parameter matrix
θ = a scalor
E_t = disturbance terms

and

$$Z_t^* = \theta \sum_{k=0}^{\infty} (1-\theta)^k Z_{t-k-1}$$

where Z_t^* = decision makers subjective expectations vector for prices and yields on which the decisions Y_t are based. Just (1974) geometrically includes quadratic lag terms to indicate the farmer's subjective evaluation of the variances of prices and yields (i.e., risk accounted for).

4. Summary

In II, C. we have progressed from single equation biological production functions (conceptually regarded as inputs to firm LP modles) to whole farm single equation production functions (which may conceptually be thought of as inputs to a spatial programming or econometric model of a regional market structure) to simultaneous equation models of a production system, biological/behavioral system, and a market system. It is sufficient to say that since economic models realistically involve many jointly dependent variables whose values are determined simultaneously, the simultaneous equation approach is preferred. Additionally, the reduced form of structural models allows for the evaluaiion of impact multipliers, i.e., the effects of changes in exogenous variables on the system can be determined.

SECTION VII

SECONDARY ECONOMIC IMPACTS DUE TO AGRICULTURAL CROP YIELD CHANGES

A. REGIONAL INPUT-OUTPUT MODELS

In put-output analysis as originally developed by Leontief (1951) is an empirically oriented multimarket analytical technique(1). Leontieff used an input-output system to determine the interdependence of various sector of the U.S. economy. I-O analysis is a simplification of the general equilibrium framework referred to in VII, B. For example, utility functions are omitted and consumer demands are usually specified as exogenous without regard to consumer market equilibrium. The production function for each industry is a constant coefficient function. The major function of I-O analysis is the determination of interdependence coefficients among the sectors which in turn may be used to predict output and employment in different sectors under varying conditions of demand(2).

In the following subsection on I-O applications, we describe two I-O models developed for local economies. Humboldt County, California is richly endowed with timber resources and natural resource amenities that appeal to residents and tourists. It is also an economically depressed economy with high unemployment and sluggish economic growth. One of the crucial issues facing decision-makers in the County is the trade-off between preservation of natural resources and their exploitation at higher rates which would stimulate economic growth and employment. I-O analysis is used as a tool to quantitatively interrelate the crucial forest products sector with the rest of the economy. Similarly, I-O analysis is an appropriate tool to use in relating air pollution effects at the farm level to secondary impacts at the agricultural processing level and in nonagricultural sectors. Welfare effects can also be determined because of the inclusion of households as an exogenous or endogenous sector. With an I-O model we can look at relationships under recent normal levels of pollution as well as project changes in sector outputs, regional income, and employment under pollution levels that are estimated to occur if standards are set.

The second I-O model discussed is a more complex and conprehensive economic-ecologic model of the Charleston, South Carolina economy. The authors are particularly interested in aiding environmental planners in issues concerning economic growth, resource utilization, and pollution generation. Such a model pertains to the air pollution-agriculture system in that the latter is also an ecologic-economic system. We might think of nonagricultural sectors such as particular industries (responsible for factory emissions) and households (auto emissions) as economic units emitting elements that adversely affect the ecological system. In agriculture the damage is manifested by crop damage of specific forms mentioned in Section V. This ecological damage is transmitted back into the economy through its effects on yields and quality.

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(1) Two general descriptive references are Isard (1960) and Heady and Candler (1958 - see references under VI, A).

(2) There are, of course, many other problems that may be handled with I-O analysis.

I-O analysis is closely related to programming procedures discussed in VI, A and VII, B, but differs in certain respects that we want to emphasize: (1) I-O analysis is positive in nature as opposed to the normative nature of programming; (2) the industry rather than the firm is the unit of production(3); (3) in I-O the initial set of activities (the product mix of the various sectors and final demand are given and solution involves determination of interdependence coefficients. In contrast, in programming models the input-output coefficients (of the firm) are given and the solution yields an optimal set of activities. On the other hand, there is one major similarity - both I-O and programming involve linear relationships and are easy to solve.

I-O may have some shortcomings in terms of oversimplification, but nevertheless has been the most widely used tool in the study of regional and interregional interdependence. Its strength lies in the detailed presentation of (1) the production and distribution characteristics of the industries of different regions and (2) the nature of the interrelationships of these industries among themselves and among these industries and other economic sectors (Isard, 1960:310).

1. Applications of I-O Analysis

a. I-O Model of Humboldt County, California

The general objective of Dean *et al*. (1973) in formulating an I-O model of Humboldt County was to provide an analytical framework that would aid public and private decision-makers to make decisions crucial to the economic development and environmental quality of Humboldt County. The issue of economic growth versus environmental quality is particularly important in Humboldt County since it contains abundant natural resources (timber, fisheries, wildlife) and because its economic vitality depends heavily on natural resource-based industries: forest products (primarily) and fisheries and recreation-tourism (secondarily). In addition, the depressed nature of the economy (leading to high average and seasonal unemployment) increases the importance of current and future decisions.

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(3) Thus, an a_{ij} coefficient in I-O gives the amount from industry i necessary to produce one unit of commodity j while in LP the a_{ij} coefficient is the quantity of the ith input required to produce one unit of output.

Thus, the specific objectives of the study were to construct an interindustry model in which natural resource-based industries were emphasized, and to make 1980 projections of the county economy under alternative output specifications, or final demand for, those natural resource industries most likely to be affected by environmental decisions(4).

The model was "partially" open in that the household sector was endogenous while exports and state and local governments were autonomous, thus constituting "final demand".

The industry data used to construct the transactions table (which ultimately contained 28 sectors) were primarily secondary, although a personal survey of businesses was carried out (mainly in the natural resources sectors) to collect cost information from certain firms. Government sector data came from both published sources and city budgets. Household output ("output" since it was endogenous) was specified as being equal to personal income, while the distribution of expenditures was based on patterns found in similar areas in the Western U.S.

Output multipliers (from the interdependence table) are used to evaluate the local output impact of increases in final demand (exports, including tourist expenditures, and nonlocal government). Typically, low output multipliers were found for industries that imported most of their inputs thus creating few backward linkages (example, food processing).

Of more interest in the Humboldt County study was the derivation of two types of income multipliers. The "Type I multiplier" was the ratio of direct plus indirect to direct household income generated by a unit increase in final demand. For example, in the Seafood Processing Industry a $1 increase in final demand (exports in this case) could lead directly to an additional $.36 local income and indirectly (through strong linkages) to an additional $.45 in local income. The Type I multiplier is equal to the sum ($.36 plus $.45) divided by $.36, or 2.25.

The "Type II multiplier" shows the ratio of direct, indirect, plus induced income to direct income generated by a $1 increase in final demand. This additional induced income is that proportion of direct and indirect increases estimated to be spent within the County, thus creating additional multiplier effects through demands on local industries.

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(4) These alternative specifications included variations in the level of cut in the lumber industry, size of catch in the fisheries industry, level of recreation-tourism activity, and level of certain government activities related to the environment.

The use of the I-O model to make 1980 projections yielded results with important policy implications for the County. It was found that prospective output increases in nonlumber sectors of the economy would be offset by decreases in lumber output because of the effects of technological change(5), employment would likely decrease from 1969 levels. This suggests that, in the absence of new employment creating firms, large amounts of nonlocal government expenditures will be required just to maintain employment levels. The bleak employment picture also raises questions about school financing (with a dwindling tax base) and suggests a policy of encoruaging out-migration.

b. Laurent-Hite Economic - Ecologic Regional Model

Recognizing that economic development creates (exports) environmental externalities and that the ecologic system in turn exports various products to the economic system(6), Laurent and Hite (1971) formulate an economic-ecologic model based on input-output analysis that incorporates both environmental and pecuniary values. The model is given empirical content by (1) developing a 31 sector I-O model for Charleston, S.C., a small coastal economy; (2) identifying and quantifying some relevant economic-environmental linkages; (3) developing environmental-income multipliers, i.e., the environmental impact per dollar of income generated by the 31 sectors. Finally, the use of the model in environmental planning (particularly resource management and zoning decisions) is discussed.

The theoretical underpinnings of the model are as follows: using a Leontief(7) model as a base, a general equilibrium approach is conceived in which materials move from the environment to the economy and then back to the environment.

The ecologic system consists of a large number of interdependent activities involving inputs and outputs. Commodities (materials) are exported from the ecologic system to the economic (processing sector) system, change form, and are then exported back to the environment(8). By conceiving of environmental resources in this way and by closing the household sector into the endogenous part of the model (hence removing the labor constraint on production), the only input constraint on production is the amount of resources available. By varying the amount of resources available and computing their effects on the economic-ecologic system, alternative resource management shemes can be evaluated.

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(5) Technological change was accounted for through labor productivity only. Wage increases of workers were assumed to match increases in average product per worker as projected using U.S. trends. The authors deemed this approach to technological change to be superior to the "best practices" approach (assuming the average firm in the future will use the technology currently employed by the most advanced firms) suggested by Miernyk (1965).

(6) This conceptual framework parallels that of Ayres and Kneese (1970) in which environmental pollution is conceived of as a materials balance problem. That is, if man uses materials from the environment he must return the residuals of these materials to the environment.

(7) The Leontief model, is, in effect, the generic name for the basic I-O model as developed in Leontief (1951, 1966) and refined by several other authors.

Operation of Model

The final version of the model closed the household and all government sectors into the endogenous part of the I-0 table. The actual I-0 table was constructed primarily on the basis of field survey data supplemented in a few cases by secondary data.

The I-0 table was used to obtain the table of interdependence coefficients and the usual multipliers were obtained showing the income effects of direct and indirect increases of export sales for given sectors.

A 17 x 28 environmental matrix (data obtained from secondary) sources was formulated to represent 17 environmental goods and their use by 28 economic sectors. One limitation of the study is that environmental emissions had to be placed in the sector to which they were most closely linearly related. Thus, auto emissions are charged to service stations rather than households(9).

The next step in the empirical operation of the model is to derive the R matrix of direct and indirect environmental impacts (see previous footnote). The direct effects come about because some sectors draw directly

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(8) The actual linkage of the economic and ecologic models was performed by post-multiplying the environmental linkages matrix (ecologic system) by the inverse matrix of the input-output model:

$$(E)\ (1 - A)^{-1} = (R)$$

where: E = matrix of inflows to and outflows from the economy to the environment;
$(1 - A)^{-1}$ = inverse matrix of I-0 model;
R = matrix of direct and indirect environmental impacts of each economic sector.

(9) There may be no way to avoid this. That is, auto emissions are not charged to the sector most responsible for them. On the other hand, exhaust emissions are more likely to increase linearly with gasoline sales than with household income. The problem is that of the linearity assumption of the I-0 model. For example, it is necessary to assume that auto emissions per dollar of household income are the same for any level of income in order to charge auto emissions to the household sector.

on resources; the indirect effects because other sectors purchase inputs from sectors that draw directly on resources. Thus, all sectors are in some way responsible for resource utilization.

The economic-ecologic model is then used to derive environmental-income multipliers, i.e., the direct and indirect environmental linkages per dollar of pecuniary income generated in the various sectors. These multipliers have significant planning implications(10). For example, a policy making body intent on maintaining supplies of regional natural resources will use the multipliers to determine which sectors can expand with the least environmental usage per dollar of income generated. Similarly, regional authorities can decide what types of industries should be encouraged to locate in the Charleston area, given existing technology and the trade-offs between income generation and resource utilization.

Resource utilization is only part of the environmental problem, the other part being emissions. Thus, planners are faced with three variables in their decisions: resource utilization, income generation, and pollution generation. If the researcher can accept the underlying assumptions of the model, it is a comprehensive tool to analyze the trade-offs between these variables. The model extends I-O analysis beyond the consideration of income and jobs as the only important development parameters(11).

The necessity of updating the environmental coefficients should be kept in mind. As mentioned in footnote 10, the estimated environmental coefficients are, at best approximations of the true coefficients. This problem is further complicated by the assumption of static technology. Thus, coefficients in the environmental matrix are based upon current intakes and discharges and each column in the I-O table represents current purchases, given the technology in place. Allowing for alternative treatment levels (for example, waste treatment) would require additional environmental matrices and the I-O model would require changes in purchasing patterns for each level of treatment. The researcher would be faced with combining the I-O table with different environmental matrices.

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(10) The implications must be considered in relation to the data used. For example, the environmental coefficients are at best "ballpark" estimates, having been generated in large part from engineering data. However, there is always the possibility of updating the coefficients as new knowledge becomes available.

(11) Laurent and Hite esentially ignore the job question. Unemployment may be low in Charleston, but in other areas, notably California, the trade-offs between environmental quality and employment creation are extremely important. The Dow Chemical decision is a notable example.

One alternative to the problems discussed above would be to include various sets of I-O and environmental matrices into a comparative static programming model in which one could analyze the effects of different levels of economic activity and changing treatment levels. The major constraint on this type of analysis would be the availability of the extensive data required.

c. Summary: Application of I-O analysis

One shortcoming of the Humboldt County model was its exclusion of an environmental matrix - especially given Humboldt County's rich endowment of natural resources. This exclusion may be due in part to the focus of the study on income and employment. The timber resource was viewed as something to be exploited, not preserved. The authors do point out that over the long run the "amenity resources" value of Humboldt County would likely improve. If so, some methods of incorporating "amenity resources" lost due to development (perhaps by means of an environmental matrix) should have been included.

I-O models are relevant to the problem of air pollution and its effects on the agricultural sector. We are interested in the interrelationships of agriculture and the non-agricultural economy, specifically in what effects the polluting non-agricultural sector has on the non-polluting (in terms of air quality) agricultural sector. From a positive viewpoint we are interested in what effects air pollution damage in agriculture has on agriculture-related sectors. We also wish to project the consequences of alleviating air pollution damage on agriculture and related sectors.

What we are losing in I-O analysis and what might be gained by a spatial equilibrium approach (see VII,B) is allowance for riskiness in farmers' decisions given the prospect of pollution damage to crops, the specification of alternative cropping activities (recognizing that pollution affects crops in different ways), and the possibility of observing welfare gains and losses due to adjustments to air pollution and projected gains and losses directly by calculating the model maximand for alternative air pollution abatement policies.

2. Methodological Appendix

a. Building an I-O Model

Regardless of whether the researcher is interested in a national, interregional, regional, or community-based model, three general stages of analysis are involved.

The first stage (and the major effort in building the model) is the construction of a transactions table. This involves defining relevant economic sectors and allocating the output of each sector to a purchasing or using sector. Since the construction of a workable model will require some aggregation of sectors, transactions (or flows) are converted to money units. The number of entries required in the transactions table is approximately the square of the number of sectors defined because of the double entry accounting of the dollar flows of all goods and services.

I-O models are referred to as open or closed depending upon whether all sectors are endogenous (closed) or whether some sectors (notably, household, government, exports) are autonomous or "outside" the system.

The second stage in the analysis is to obtain a table of input-output coefficients in which the elements relate the amount of inputs (in dollars) required from each sector to produce a dollar's worth of output for any given sector. The basic assumption made here is that the coefficient is measured from a single (and current) observation of the ratio between the transaction of one sector to another and the gross output of the receiving sector.

The third stage of I-O model building is to develop a table of interdependence coefficients. Each coefficient summarized both the direct and indirect dependence of one sector on another. Although the interdependence table may be summarized in several ways, the most common is to determine output multipliers (by vertical summation of the columns). These give the total value of inputs generated from all sectors associated with a one dollar sale to final using sectors. Other types of multipliers are income and employment multipliers and will be defined in a later "Applications of I-O Analysis" section.

b. Example of an Open Static I-O System

We will illustrate the basic model by means of an illustration found in Gass (1969).

The following is an input-output table of a 3 industry economy (railroad, steel, coal):

	sales to RR	sales to steel	sales to coal	sales to other	sales to final demand	Total sales
RR sales	X_{11}	X_{12}	X_{13}	X_{14}	Y_1	X_1
steel sales	X_{21}	X_{22}	X_{23}	X_{24}	Y_2	X_2
Coal sales	X_{31}	X_{32}	X_{33}	X_{34}	Y_3	X_3
Other sales	X_{41}	X_{42}	X_{43}	X_{44}	Y_4	X_4

The elements may be interpreted as follows (examples):

X_{12} = sales of rail road industry to steel industry

X_{32} = sales of coal industry to steel

Y_2 = sales to steel industry to final demand

All sales are in dollars. Final demand in this case includes foreign trade, government operations, and households. The definition of final demand may vary as one or more elements may be considered as endogenous instead of autonomous. Also, such items as inventory accumulation and net investment could be part of final demand or could be classified as producing sectors. Actual classification depends upon objectives of the research. X_1 = final bill of goods of railroad industry. Each row may be interpreted as a sales row; each column as a purchases column.

By specifying: $X_i > 0$
$X_{ij} \geq 0$
$Y_i \geq 0$

we can summarize the table in a system of linear relationships for a base period:

$$\begin{aligned} X_1 - X_{11} - X_{12} - X_{13} - X_{14} &= Y_1 \\ X_2 - X_{21} - X_{22} - X_{23} - X_{24} &= Y_2 \\ X_3 - X_{31} - X_{32} - X_{33} - X_{34} &= Y_3 \\ X_4 - X_{41} - X_{42} - X_{43} - X_{44} &= Y_4 \end{aligned}$$

The first eauation (for example) states that the total sales of the railroad industry minus sales to individual industries equals what is left over for final consumers.

Now let us define an input-output coefficient as:

$$0 \leq a_{ij} = \frac{X_{ij}}{X_j} = \text{amount of industry i necessary to produce one unit of commodity}$$

Since $X_{ij} = a_{ij}X_j$ we can substitute for the X_{ij}'s in our base period system:

$$\begin{aligned} X_1 - a_{11}X_1 - a_{12}X_2 - a_{13}X_3 - a_{14}X_4 &= Y_1 \\ X_2 - a_{21}X_1 - a_{22}X_2 - a_{23}X_3 - a_{24}X_4 &= Y_2 \\ X_3 - a_{31}X_1 - a_{32}X_2 - a_{33}X_3 - a_{34}X_4 &= Y_3 \\ X_4 - a_{41}X_1 - a_{42}X_2 - a_{43}X_3 - a_{44}X_4 &= Y_4 \end{aligned}$$

In matrix form this system can be written as:

$$(I - A)\,X = Y$$

where $A = [a_{ij}]$; $X = \begin{pmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \end{pmatrix}$; $Y = \begin{pmatrix} Y_1 \\ Y_2 \\ Y_3 \\ Y_4 \end{pmatrix}$

and (I - A) is known as the Leontief matrix.

With this linear structure of our simple economy we can determine a production vector X which satisfies our final demand vector Y. That is find X such that:

$$X \geq 0$$

$$(I - A)\, X = Y$$

where: A = I-O coefficient matrix.
Solution of the system for the required levels of X to meet final demands Y is given by:

$$X = (I - A)^{-1}\, Y$$

We can also formulate this as a programming problem by allowing production to fall short of final demand requirements, i.e.,

$$(I - A)\, X \leq Y$$

Thus, we introduce a vector of slack variables W:

$$(I - A)\, X + W = Y$$

In addition, we introduce an objective function c'X. This function may represent total profit or the output of one industry or some combination of industries (or for a given regional problem we might want to maximize total employment).

Additionally, we will specify that the production (activity) level of each industry is constrained by known capacity levels L, i.e., $X \leq L$. Another vector U will represent unused capacity. Finally, allowing for the stockpiling of finished goods available from production in previous periods we introduce a vector S.

Thus, our entire problem can be stated in LP form as:

$$\begin{aligned} &\max\ c\,X \\ &\text{subject to:}\quad (I - A)\, X + W = Y - S \\ &\qquad\qquad\qquad X + U = L \\ &\qquad\qquad\qquad\quad X \geq 0 \end{aligned}$$

c. LP Formulation of a Dynamic I-O System

Dynamic input-output theory is a natural extension of the static and comes from consideration of intersectoral dependence involving time lags or rates of change over time. The theoretical basis is provided by the relations between stocks and flows in a system of structural relations.

In a study concerning the effects of air pollution in agriculture the researcher would want to know both the static and dynamic direct and indirect effects of crop yield changes due to air pollution (and subsequent changes in crop mix, total output, producers' and consumers' surplus) on such parameters as regional employment, gross regional product, and the output and employment levels of industries interrelated to agriculture.

In other words, how will current decisions to limit air pollution emissions affect agriculture and the emitting sectors directly and in future time periods? Interrelated sectors (for example, agricultural processors and suppliers to emitting firms) will be affected indirectly in current and future time periods. Thus, current air pollution standards have important implications for regional development.

We may extend the static model example above to multiple time periods by making the following changes(12):

n = number of time periods considered
$t = 1, 2, \ldots, n$ = particular time periods
$X_t = (X_{t1}, X_{t2}, \ldots, X_{tm})$ = production vector
$Y_t = (Y_{t1}, Y_{t2}, \ldots, Y_{tm})$ = final demand vector
$S_t = (\qquad\qquad)$ = storage vector
$U_t = (\qquad\qquad)$ = unused capacity vector

The major change is that we must provide for the expansion of capacity to meet future final demand requirements. That is, we must allow for population and economic growth.

Let: V_t = vector of additional available capacities
B = matrix of capital coefficients in which the j^{th} column represents the inputs from each industry necessary to build an additional unit of capacity for the j^{th} industry.

Then, the i^{th} row of the product $B\,V_t$ represents the amount of the i^{th} industry's production used to build additional capacity in time period t for all industries.

We can summarize the new conditions as follows:

$$(I - A)\,X_t + S_{t-1} = Y_t + B\,V_t + S_t \qquad (1)$$

$$X_t + U_t = L + \sum_{q=1}^{t-1} V_q \qquad (2)$$

Equation 1 states that total output plus previous stocks equals the final demand and capital expansion requirements for output plus the current period's unused stocks. Equation 2 states that total used and unused production equals initial production capacity plus previous increases in production capacity.

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(12) Model given in Wagner (1954).

Equations 1 and 2 may be rewritten in the format of typical LP constraints:

$$(I - A) X_t - B V_t - S_t + S_{t-1} = Y_t \qquad (3)$$

$$X_t - \sum_{q=1}^{t-1} V_q + U_t = L \qquad (4)$$

d. Problem Areas in I-O Analysis

Some of the problem areas in I-O analysis will be mentioned in the description and discussion of two regional I-O studies contained in subsequent sections. In this section we mention two well known problems: aggregation and the assumption of constant production coefficients.

The problem of aggregation is probably the most significant one faced in a prospective I-O study. By aggregation, we mean the process of combining industries into the economic sectors to be analyzed. If we aggregate the economy into a fairly small number of sectors (that may be consistent with time and funds available)(13), we may lose important details of specific products and industries. On the other hand, an appropriately disaggregated model for a given set of research objectives will be very expensive with respect to clerical and computational needs, although the researcher gains in predictive reliability.

There are several alternative bases for aggregation. One might aggregate industries which have similar production functions, or similar rates of technical change, or that feed into homogeneous consuming industries. General procedures that may be followed are to define sectors so as to minimize intersector transactions and to maintain similarity in input structures among the products of any sector. Unless some means is found to break down aggregates into flows to industries, aggregation can be no more refined than that allowed by available data sources.

The assumption of constant production coefficients is the most limiting assumption of I-O analysis. Since production coefficients largely reflect existing technological relations, the assumption of constant coefficients means unchanging or constant technology. The use of constant coefficients does not reflect real world conditions in the following areas:

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(13) As the number of sectors decreases the tremendous data collection job necessary for I-O studies becomes less costly and time consuming. Simpson and Adams (1975) have shown how to selectively disaggregate the transactions or technical coefficients matrix of existing I-O studies in order to determine output and income multipliers for product lines.

(1) Economies of scale (present in most industries);
(2) Localization external economies (i.e., similar plants agglomerate in one place);
(3) Urbanization external economies (dissimilar plants agglomerate in one place);
(4) Price changes (lack of relative price changes means that substitutions among inputs cannot be induced);
(5) Technological change: where technological advance leads to a regular pattern of change in input requirements for an industry, coefficients may be reasonably extrapolated; where change is unpredictable (including the introduction of new products), the use of the model for projection is limited;
(6) Finally, projections made on the basis of constant coefficients limits the use of the model for projection(14);
(7) Finally, projections made on the basis of constant coefficients abstract from the roles of expectations in the behavior of entrepreneurs, governmental units, and consumers.

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(14) Note that the introduction of pollution control policies, if they are efficiently implemented, implies technological change.

B. REGIONAL SPATIAL PROGRAMING MODELS

Among spatial aspects of agriculture of traditional interest to agricultural economists are land-use patterns, interregional competition and supply potential. To these we can add topics of contemporary interest such as the interregional effects of water quality and quantity changes, energy supplies, and air quality.

Spatial models may be broadly defined as any theoretical construct having space as one component (Bawden, 1964). Economic models that include space as a component generally involve several commodities and describe one or more of the following activities: regional location and level of production (both primary (farm) and secondary (processing) stages); regional level of consumption of final goods; relative and absolute prices. The model formulations describing these activities include plant location models, regional activity analysis models, transportation models, and spatial equilibrium models. These formulations, in turn, provide several types of information: efficient shipping patterns (implying efficient location patterns), efficient production patterns and resource allocation, forecasts of shipping and production patterns, forecasts of regional storage, comsumption, and prices, and the effects of changes in exogenous variables on the models.

Spatial models, as applied, have attempted to provide information on the following areas(1):

(1) Allocation of production and land-use under free market (competitive equilibrium) conditions versus the allocation under land retirement and/or marketing quota programs;
(2) The costs of alternative government programs;
(3) The effects on production, land-use, and cropping patterns of technological change, changes in export and/or domestic demand, and energy shortages;
(4) The impacts of alternative development projects;
(5) Optimal sizes, numbers, and location of processing plants.

A few general remarks are pertinent concerning the difference between spatial models and the supply response models discussed in VI, A. Spatial models typically use a region as a basic producing unit; supply response models use the representative farm. Supply response models attempt to predict market supply under a given set of market conditions, usually ignoring interactions between farms in different regions or in the same region. Spatial models usually take explicit account of interregional competition by including demand restraints and allowing for interregional shipment of commodities. Additional, and more specific differences in spatial and supply response models will be discussed in the subsequent sections.

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(1) Heady and Hall (1968) provide a brief review of spatial models used in the 1958 - 1966 period. The basis of these models and post - 1966 to present models was provided in Samuelson (1952), Beckmann and Marschak, (1955) with later developments provided by Takayama and Judge (1964).

There are also differences among spatial models that are pertinent to analyzing air pollution effects on producers, processors, and consumers. Following Bawden (1964) we may classify spatial models as standard equilibrium or activity analysis models. The standard equilibrium model is characterized by:

(1) discrete producing and consuming regions;
(2) quantities supplied and demanded may be predetermined or endogenous to the system;
(3) unit transfer costs are specified between producing and consuming points;
(4) given that production and consumption are endogenous, equilibrium quantities of production, consumption, imports and exports, and absolute prices are specified under the assumption of profit maximizing behavior;
(5) the solution is consistent with regional and total profit (net social product) maximization and transfer cost minimization;
(6) such models may incorporate many commodities interrelated in supply or demand, demand functions for factors, multiple time periods, and storage activities.

The activity analysis model (most spatial models have been of this type) has the following characteristics:

(1) discrete regions, but can determine market boundaries within model;
(2) predetermined or endogenous demand;
(3) generates own supply relationships instead of relying on explicit supply functions as in standard equilibrium model;
(4) regional resources fixed or mobile depending on time horizon;
(5) physical plants fixed or variable;
(6) net consumer surplus can be maximized depending upon specification of the objective function.

The general attributes of each model are similar with the main difference residing on the specification of the supply process (see (3) above). Furthermore, the supply functions in standard equilibrium models can be estimated by regression analysis, or derived from linear programming (LP) or recursive programming (RP).

The advantages of exogenously estimated supply relationships are probably the most significant in short-run prediction. Since the production process in standard equilibrium models does not have to assume efficient production, estimated supply functions can account for the level and variability in production costs among regions. On the other hand, the activity analysis model takes as given the production relationships, and factor and product prices. Under a profit maximizing assumption, it can probably make better long run predictions because short-run inflexibility factors are no longer important.

The research implications of these differences are as follows: standard equilibrium models with econometrically estimated supply equations would be best for analyzing the short-run effects of changing government programs (price supports, acreage allotment) or other exogenous variables such as pollution standards. However, the long run effects of such exogenous changes would better be analyzed by either activity analysis or standard equilibrium models with supply derived by LP or RP methods.

One further difference in spatial models should be noted: the linear versus nonlinear model. In the linear version we assume that demand (whether regional or national) is known. The appropriate objective function is one of minimizing the production and transport costs of a final bill of goods(2).

The nonlinear case occurs when prices and quantities demanded are not given as a priori knowledge, but instead are variables whose values we want to determine simultaneously with supply. Demands are represented by continuous linear functions.

1. Nonlinear Spatial Programming Model: An Example

Before outlining the basic model, we note that the same assumptions and limitations apply to spatial programming models as applied to the programming models discussed in VI, A. We are extending the firm and aggregate supply response models in VI, A to the whole market, i.e., producers and consumers. The three major differences between the firm and market models are that in the latter we have homogeneous production regions, endogenous demand, and a maximand of net social payoff (instead of net revenues).

We will define the following symbols and equations according to those in Hall et al. (1968):

K consumption regions; H production regions

b^{hk} = vector of primary resources for production region h in consumption region k
X^{hk} = vector of output levels for production region h in consumption region k
A^{hk} = input/output matrix relating b^{hk} to a unit of X^{hk}
p^k = vector of prices for elements of d^k (see below)
C^{hk} = vector of costs associated with X^{hk}
U^{hk} = vector of imputed values of primary resources, b^{hk}
S^{jk} = vector of shipments from market j to k
t^{jk} = vector of unit shipping costs associated with S^{jk}

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(2) Among the formulations of this model are Egbert and Heady (1961) and Heady and Whittlesey (1965).

Linear demand system: $d^k = d_o^k + D^k p^k$

d^k = vector of quantities demanded
d_o^k = vector of constants
D^k = matrix of constants (negative semidefinite)

The problem:

$$\text{MAXIMIZE} \quad f(X^{hk}, p^k, U^{hk}, S^{jk}) = \sum_{k=1}^{k} \{(d_o^k + D^k p^k)' p^k - \sum_{h=1}^{H} C^{hk} X^{hk} - \sum_{h=1}^{H} U^{hk} b^{hk}\} - \sum_{j \neq k}\sum t^{jk} S^{jk} \qquad (1)$$

subject to:

$$A^{hk} X^{hk} \leq b^{hk} \qquad (2)$$

$$p^k - (A^{hk})' U^{hk} \leq C^{hk} \qquad (3)$$

$$D^k p^k - \sum_{j=k} (S^{jk} - S^{kj}) - \sum_{h=1}^{H} X^{hk} \leq - d_o^k \qquad (4)$$

$$p^j - p^k \leq t^{kj} \qquad (5)$$

$$p^k - p^j \leq t^{jk} = t^{kj} \qquad (6)$$

$$X^{hk}, U^{hk}, S^{jk}, P^k \geq 0 \qquad (7)$$

Interpretation of equations:

(1) Quadratic objective function

$(d_o^k + D^k p^k)' p^k$ = Total revenue

$C^{hk} X^{hk}$ = Production costs

$U^{hk} b^{hk}$ = Imputed land rent, etc.

$t^{jk} S^{jk}$ = Transportation costs

The inclusion of the imputed values of scarce resources in the objective function (U^{hk} in (1)) makes this a self-dual problem in which there is zero profit at the optimum.

Given that (1) is concave (since D^k is negative semidefinite) and that the constraint set is nonempty, the problem is solved using quadratic programming (QP)

(2) Resource use cannot exceed availability
(3) Marginal returns from an activity must be less than or equal to marginal costs
(4) Product plus net imports must be greater than or equal to demand
(5) and (6) Conditions for trade equilibrium.

2. Applications

The basic aggregate programming model discussed in this section involves the interface of a market demand structure with a supply model to obtain simultaneous determination of the equilibrium levels of production and prices. Under the assumption of a perfectly competitive environment Samuelson (1952) showed that the appropriate objective function is the maximization of net social payoff (NSP) or the sum of producer and consumer surpluses (PS + CS)(3)

Takayama and Judge (1964) extended this objective function to obtain a quadratic programming solution for multiproduct markets. They also showed how the model could be modified to include multiple time periods. Duloy and Norton (1973) showed how LP approximations of QP solutions could be obtained in sector models. Hazell and Scandizzo (1973, 1974) modify the Duloy-Norton objective function to incorporate risk averse behavior, i.e., assume that farmers behave according to an E-V decision criterion(4).

The NSP (= PS + CS) maximand specification ensures that the optimal solution will be a competitive market equilibrium and allows for the identification of gainers and losers due to policy actions. For example, allowing air pollution to continue at current or increased levels (assuming that standards will not be set immediately) may lead to adverse soical effects, that is, on producers or consumers, or both. On the other hand, air pollution abatement hypothetically may lead to a net social gain but with consumers gaining (through increased production and lower prices) at the expense of producers (expanded supply and inelastic demand leading to lower prices and revenues). The possibility may then be raised of compensation of the losers by the gainers.

Risk inclusion is important because in deterministic risk free models the production of high risk crops is typically overestimated. Variations in income associated with any crop are, of course, due to yield and/or price variability. By specifying risk averse behavior, the solution will avoid high acreages of high risk crops. In addition, given that many high risk crops are also high value crops, risk inclusion will prevent overstatement of the returns to investment.

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(3) Samuelson developed this welfare maximization problem in the context of spatial equilibrium among spatially separated markets. In his analysis of interregional trade, back-to-back graphs (with a positively sloping excess supply function in one region) are used in which social payoff in any region is the area under the excess demand curve (which is equal to the area under the excess supply curve but opposite in sign). In the absence of better measures, PS and CS are measure the dollar values of producers' and consumers' welfare.

(4) Hazell and Scandizzo (1974) develop the appropriate aggregate objective function when farmers are assumed to maximize E-V utility (see VI, A for further discussion of the E-V criterion). Hazell and Scandizzo (1973) show how the objective function may be modified to handle other probabilistic decision criteria: notably the type in which the risk aversion coefficient is measured in standard deviation units.

Again, there are implications pertaining to the air pollution problem. Given levels of air pollution are going to alter the risk patterns of crops in different ways since some crops will be more adversely affected than others. By incorporating risk averse behavior we hope to account for these differential risk patterns and derive realistic cropping patterns.

a. Duloy - Norton Model

The Duloy-Norton (1973) model (CHAC) is a comparative static risk-free model of Mexican agriculture. Many of the attributes of this model apply equally to the Adams (1975) model of California agriculture which is discussed in section b.

The production system in the CHAC model is composed of 20 geographic submodels. Each is solved to yield returns on fixed investments. For example, in low income agriculture, investments in new machinery or new seed (i.e., new technology) are particularly important. In the aggregate sector model, the effects of interregional competition on estimated returns are examined.

The sector model describes the production imports, domestic demand, and exports of 33 short-cycle crops. The production of these crops in the 20 aceas is represented by 2300 different production techniques.

The demand structure is price dependent (i.e., price is a function of quantity), hence market clearing prices are endogenous. With a few special exceptions, demand functions are national. The general benefits of the price endogenous demand structure are that it prevents overspecialization in cropping activities (the negatively sloped demand curves serve as constraints), thus enabling the model to more realistically portray actual conditions, and it permits appraisal of the distribution of benefits between consumers and producers accruing from increases in agricultural production. Of particular interest to a developing economy, this specification also allows capital-labor substitution to occur through changes in domestic demand. In the CHAC model such substitution can also occur through changes in technology or through changes in the commodity mix of exports. Finally, the price endogenous demand structure allows for examination of the welfare effects of price supports, import quotas, product price taxes, export subsidies, and varying exchange rates. The effects of these alternative government policies on profits, employment and other variables may also be analyzed(5).

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(5) The perfectly competitive model can also be modified to represent a monopolistic supplier in which case the effects of government policies will be substantially different.

Note also that the demand structure is not completely interdependent. That is, demand functions are defined by commodity groups and substitution is allowed *only* within groups, not among groups (i.e., cross-price elasticities equal zero).

The Duloy-Norton objective function (and the risk free Adams objective function) are conceptually written as follows:

(1) Assuming linear demand functions and zero cross-price elasticities we have the demand function:

$$P = a + B\ q$$

where P = price vectro
q = quantity vector
B = negative diagonal matrix of slope coefficients

(2) Assume the following vector of total cost functions:

$$c\ (q)$$

(3) Thus, under perfect competition the objective function is:

$$Z = q\ [a + 15\ B\ Q\ ] - c\ (q)$$

and the first order conditions are (obtained by setting $\frac{dZ}{dq} = 0$):

$$P = a + B\ q = c'\ (q) = \text{marginal cost (MC)}$$

(4) We can decompose Z into the sum of two things:

$$\text{Consumer Surplus (CS)} = .5\ q'\ [a - P] = .5\ q'\ B\ q$$

$$\text{Producers' Surplus (PS)} = q'\ P - c\ (q) = q'\ [a + B\ q] - c\ q$$

That is, the objective function is net social payoff *or* the sum of CS and PS.

Operationally, the net social payoff maximand (NSP) in the Duloy-Norton model may be verbally represented as:

maximize Z = [sum of CS and PS] + [export earnings] - [import costs]
- [total labor costs] - [total long term capital costs]
- [interest on short term debt] - [seed costs] - [chemical costs]
- [draft animal service costs] - [gravity water costs]
- [well water costs] - [increments in gravity water cost]
- [increments to well water cost] + [district crop price differences]

The farmers' total profit function serves as a contraint to the NSP function and is identical to the NSP function except for the following differreces:

(1) maximized profit instead of NSP;
(2) gross revenue from domestic sales replaces sum of CS and PS;
(3) interest on long term capital replaces total long term capital costs;

To obtain total farm income add the following term to the profit function:
(1) farmers wage income;

To obtain total sector income, do the following:
(1) delete total labor costs;
(2) remove labor cost element from interest on long term capital.

b. Adams Model

Adams (1975) formulated a short run comparative static QP model that analyzes the effects of alternative commodity price levels, energy availability levels, and energy input levels on irrigated acreage, total output, regional cropping patterns, the demand for land, water, fuel, and other inputs, and the resulting changes in producer and consumer welfare. Since the spatial allocation of production was not of concern to Adams, there are no transportation costs included.

The model encompasses 19 crops (hence, 19 demand functions extended to 28 to include appropriate seasonal effects) and 14 production regions (extended to 28 to accomodate 2 soil types). Each region is defined according to homogenous climate, water, and soil types. For the air pollution problem we might define production regions according to homogenous pollution levels or air basins as well.

Yield response functions were developed to permit evaluation of the impact on yields of reductions in fertilizer. The matrices of technical coefficients (input-output) are formulated to reflect the lower yields due to fertilizer reductions. Similarly, we propose the use of yield response functions to evaluate the effects on yields of alternative pollution levels.

As in the Duloy-Norton model, the demand structure was price endogenous with zero cross-price elasticities. By estimating the demand relations, slope coefficients and price flexibility coefficients were derived(6). Shifts in intercept terms were introduced to reflect changes in the level of demand. Such changes might occur from population increases or increases in gross domestic product or per capita income.

Adams' objective function is a synthesis of the Duloy-Norton function and the Hazell-Scandizzo work on risk incorporation. That is, yield variability coefficients (previously estimated in another study) act as proxies for the subjective risk faced by farmers. The price-demand structure is assumed to be nonstochastic. This approach understates the actual subjective risk faced by farmers, but such data may be obtained only by interview which would be very time consuming and costly in a statewide study. On the other hand, in a regional sutdy based on representative farms, interview procedures would be feasible.

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(6) Elasticity coefficients may be derived under very restrictive assumptions. Or, as Duloy and Norton did, own price and income elasticities may be borrowed from other studies.

Adams' risk free objective function which maximizes NSP may be written as:

$$\text{Max } Z = \sum_{i}^{r} C_i \sum_{j}^{s} \sum_{k}^{t} X_{ijk} + \sum_{i}^{r} d_i \sum_{j}^{s} \sum_{k}^{t} X_{ijk}^2 - \sum_{i}^{r} \sum_{j}^{s} \sum_{k}^{t} T\ V\ C_{ijk}$$

where: C_i = intercept of demand function for crop i
d_i = slope coefficient of demand function for crop i
X_{ijk} = production of crop i in region j by process k
TVC_{ijk} = total variable cost (exclusive of land and management) of producing a unit of crop i in region j by process k.
r, s, t, are upper limits on commodities, regions and processes.

The objective function with risk included may be written in matrix notation as:

$$\text{Max } Z = C\ X + .5\ X'DX - TVC - \phi\ TVC$$

Thus, it is the same as the risk-free function except for the appearance of a vector of risk coefficients (ϕ) as an additional cost element. Risk in this case may be interpreted as the additional expected return demanded by farmers in return for assuming risk. The risk cost for each crop is the product of variable cost and yield variability.

The constraints in the Adams model are soil acreage by type, applied irrigation water, several purchased inputs (gasoline, diesel fuel, nitrogen fertilizer, pesticides), institutional (total production and regional processing capacity), and the usual non-negativity conditions.

The procedures for obtaining a solution differ between the Adams and Duloy-Norton models. Adams uses quadratic programming (QP) to obtain a competitive equilibrium solution while Duloy and Norton use LP approximation procedures. Their technique is similar to the grid linearization method of separable programming. Hazell and Scandizzo also propose methods of linearizing quadratic terms to ease computional problems. However, if a QP algorithm is available, large scale quadratic problems may be solved fairly easily, thus precluding the necessity of using LP approximations.

Some of Adams' results and their implications will be briefly mentioned to illustrate the benefits of using the NSP objective function. By incorporating risk into the model, Adams found that consumer surplus (CS) was reduced (from the non-risk case) by 22 percent while producers' surplus (PS) was reduced only 1.5 percent(7). These relative changes were due to farmers' decisions to increase the production of less risky (and price elastic) field crops while cutting back on high risk (but price inelastic) vegetable crops.

The impact of severe energy shortages varied in their distributional impact. Sharp cutbacks in fertilizer availability significantly reduced PS, but CS stayed about the same. This has environmental policy implications. For example, the cost of a policy to reduce ground and surface water nitrate concentration by reducing the amount of nitrogen fertilizer input would be borne by producers. This raises the question of compensation.

The effects of total (fertilizer, fuel) energy cutbacks and increased fuel costs would be borne by consumers (CS decreases) while PS would actually increase. This suggests that a policy of fuel cost subsidies would be of great benefit to consumers.

To summarize the study the following essential elements of the model are listed:

(1) specification of 28 production regions;
(2) specification of seasonal or annual price-forecasting equations for 9 vegetable and 6 field grain crops;
(3) derivation of nitrogen fertilizer response functions;
(4) identification and calculation of non-land costs of production for all crops -- including yield variations;
(5) constraint identification: physical, energy, institutional (estimated);
(6) determination of input requirements for each crop;
(7) determination of regional cropping patterns and yields;
(8) derivation of input-output coefficients by cropping activity;
(9) development of future projections for all of the above.

The main attributes of the model are:

(1) risk inclusion;
(2) sensitivity to changes in price-quantity slopes and intercept values;
(3) identification of gainers and losers.

Among the limitations of the model are:

(1) limited to California, excludes rest of U.S.,
(2) not recursive (thus leading to errors in projections; however, recursive models of this size are currently unfeasible computationally);
(3) lack of cross-price effects; these can be handled computationally but are difficult to estimate;
(4) exports could be handled better, i.e., by using a Duloy-Norton kinked demand curve.

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(7) PS defined as returns to land and management. CS equal to total value of objective function (Z) minus net revenues to producers.

3. Summary

In VII, B we have seen that spatial programming modles can be applied to a wide variety of regional research topics. The general form of the models discussed in "Applications" involves the interface of a market demand structure with a supply model to obtain simultaneous determination of the equilibrium levels of production and prices. The appropriate objective function was the maximization of net social payoff (sum of producers' and consumers' surplus) which facilitates measuring welfare gains and losses due to alternative policy actions. With the additional feature of risk incorporation, such models are capable of providing information of use to decision makers. We can readily derive alternative regional outcomes due to varying such parameters as cost coefficients, input-output relationships, and resource and institutional constraints. Changing air pollution levels, whether by natural occurrence or policy action, may be indicated by the investigator by altering these parameters. Subsequent changes in output, cropping pattern, profits, and consumer surplus may then be generated by the model.

SECTION VIII

OVERALL IMPACTS ON CONSUMERS DUE TO CROP YIELD CHANGES

In this section we will review some basic concepts in supply and demand theory with the objective of elucidating the theoretical underpinnings of the empirical techniques discussed in Section VI and Section VII(1). An important concept to keep in mind during the discussion in Section VIII is that of interrelationships: of prices; quantities demanded and supplied; among consumers; among producers; between consumers and producers. It should become clear that when a given policy action is taken, the impact reverberates throughout the economic system.

Subsection A focuses upon market supply functions as derived from the marginal cost functions of individual firms. In subsection B we concentrate upon market demand as derived from the aggregation of individual consumer demands. Several demand concepts are discussed: direct and cross-price elasticities, income elasticity, and income and substitution effects. In subsection C we discuss the relevance of price and supply stability analysis to measuring the welfare effects of policy changes. For illustrative purposes subsection C, 1, formulates air pollution effects in agriculture as a problem in welfare economics.

The supply side (and underlying production relationships) of the market system has been the focus of much of the review thus far. Section V deals with the biological aspects of air pollution damage to crop yields. In Section VI, beginning with the assumption that pollution-yield relationahips are available in forms that may be incorporated into production relationships, we reviewed optimizing and non-optimizing models of the firm as well as aggregate production/profit relationships. In Section VII we concentrated on two formulations of regional-market models: input-output and spatial programming models. In input-output models, industry sectors are the units of measurement and we saw that demand was represented in alternative ways: in the closed system, all sectors were endogenous including households, government, exports; in open models, one or more of these sectors was autonomous. Spatial programming models were found to have several attributes: incorporation of endogenous demand relationships, allowance for risk may be built in, and given certain assumptions and the specification of the model, the appropriate maximand was net social payoff or the sum of consumers' and producers' surplus (CS + PS).

Thus, in Section VII we brought the consumer into the system. For example, in Adams' (1975) quadratic programming model of California agriculture, price dependent demand equations were specified for the crops under study. Given the objective function of maximizing CS + PS and the additional assumption that these concepts can measure consumer and producer welfare, Adams examined the distributional effects of alternative energy prices and policies.

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(1) Basic concepts of the theory of the firm and demand theory may be found in any good economic textbook. Among others, see Henderson and Quandt (1971) and Ferguson (1969).

A. SUPPLY

Thus far in this review we have spoken of supply functions in the following contexts: supply function of the firm as derived from a programming model or from a production function; aggregate supply function as derived from an aggregate programming model or aggregate production function; statistically estimated aggregate supply function.

For purposes of defining the elasticity of supply, we set forth the economic rationale underlying the empirically derived supply functions mentioned above(2). Specifically, the short-run marginal cost curve of the firm may be derived from its marginal product curve under the assumption of constant input prices. That portion of the firm's short-run marginal cost curve lying above the average cost curve constitutes the firm's supply curve. Although the industry's short-run supply curve is only on approximation of the horizontal summation of the marginal cost curves of firm's in the industry (approximate, because even under perfect competition, the simultaneous expansion of output by all firms will bid up input prices), it is positively sloped, meaning that quantity supplied varies directly with price.

The *elasticity of supply* may then be defined as the relative responsiveness of quantity supplied to changes in price. To expand upon this concept we may say that *inelastic supply*(3) means that for a given change

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(2) Empirically, the general supply response relationship may be expressed as follows:

$$q_t = f(P_t, PC_t, A_t)$$

where: q_t = amount of commodity supplied in time t
P_t = price of given commodity
PC_t = prices of competing commodities
A_t = technological change and/or institutional influences

In the long run, the dynamic supply relationship may be expressed as:

$$q_t^* = f(P_t^* , A_t)$$

where Q_t^* and P_t^* are *desired supply* and *expected prices* respectively. Since these are unobservable, assumptions must be made as to how producers determine *actual supply* and form their price expections.

(3) In terms of the values of coefficients (letting ε = elasticity of supply), inelastic supply means $\varepsilon < 1$, unitary elastic supply means $\varepsilon = 1$, and elastic supply means $\varepsilon > 1$.

in price, supply responds less than proportionally. Unitary supply elasticity occurs when supply responds exactly proportionally to a given change in price. Elastic supply means that for a given change in price, supply responds more than proportionally.

B. DEMAND

The principle assumption upon which the theory of consumer behavior is constructed is that a consumer attempts to allocate his limited income among available goods and services so as to maximize satisfaction (or utility). Given this assumption and the properties of indifference curves(4), individual demand curves may be derived. For almost all goods individual demand curves are negatively sloped -- that is, quantity demanded varies inversely with price.

There are four basic determinants of individual demand: (1) the price of the commodity determines quantity demanded given the level of demand; (2) money income is one of three determinants of the level of demand; (3) tastes (determines level); (4) prices of related commodities (determine level). These four factors jointly determine quantity demanded and the level of demand, and market demand for a specific commodity equals the horizontal summation of the individual demands of each consumer. Given this negatively sloped market demand function and following a brief mathematical digression we can proceed to define the following concepts: price elasticity and cross-price elasticities of demand, income and substitution effects, and income elasticity of demand.

1. Mathematics of Demand Theory

Mathematically, the following function represents utility maximization subject to a budget constraint for an individual consumer.

$$U = f(q_1, \ldots\ldots, q_n) + \lambda(Y - \sum_i^n P_i q_i)$$

where: $(q_1, \ldots\ldots, q_n)$ = commodities
Y = consumer's fixed income
P_i = commodity prices
λ = Lagrange multiplier

By setting the first order partial derivatives of U (   ) with respect to q_i and λ_i ($\partial U/\partial q_i = \lambda P_i$ and $Y = \sum P_i q_i$) equal to zero, the first order conditions can be expressed as the equality between the rate of commodity substitution and price ratios for any pair of commodities.

Assuming the second order conditions hold, the individual demand functions can be expressed as:

$$q_i = f(P_1, \ldots\ldots, P_n, Y), \quad i = 1, \ldots\ldots, n$$

---

(4) An indifference curve forms a locus of all commodity combinations from which a consumer derives the same level of satisfaction.

By aggregating these n equations over all consumers the market demand functions may be derived. It should be clear that this system of equations implies that all commodities are interrelated.

If the researcher's interest focuses on particular commodities (or even a single one), there are alternatives to estimating the whole set of equations. Under the assumption of want independence(5), the demand function for a given commodity can be expressed as:

$$q_i = f(P_i,\ P_i^{oc},\ Y)$$

where P_i = price of i^{th} commodity

P_i^{oc} = prices of other commodities affecting i^{th} commodity

Y = income

The corresponding market demand function is

$$Q_i = f(P_i,\ P_i^{oc},\ Y,\ A)$$

where $Q_i = \sum_i q_i$

$Y = \sum y$ over all consumers

2. Price Elasticity of Demand

The price elasticity of demand may be defined as the responsiveness of quantity demanded to changes in price. For any $q_x = f(P_x)$, the direct point price elasticity e_{xx} is(6):

$$e_{xx} = -\frac{\Delta q}{q} \Big/ \frac{\Delta P}{P} = -\frac{\Delta q}{P} \cdot \frac{P}{q}$$

Demand is considered to be price inelastic, unitary elastic or elastic depending upon the value of e. If e < 1, demand is inelastic and a given change in quantity demanded. If e = 1, demand is said to be of unitary elasticity and a given change in price will be accompanied by a proportionately equal change in quantity. If e > 1, demand is elastic and a given change in price will be associated with a proportionally greater change in quantity demanded.

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(5) See George and King (1971) for a comprehensive review of both the theory and empirics of demand. They also estimate a alrge system of demand relationships.

(6) In mathematical terms; given the demand function for commodity i:

$$q_i = f(P_1,\ P_2,\ .\ .\ .\ .\ .\ ,\ P_m,\ Y)$$

The direct price elasticity is: $e_{xx} = -\frac{\partial q_i}{\partial P_i}\frac{P_i}{q_i}$

Two basic factors determine the direct price elasticity of demand: the availability of substitute goods and the number of uses to which the goods may be applied. As the number of substitute goods and the uses to which a given commodity may be put increase, so does the value of the elasticity coefficient.

Generally farm products have low elasticities, that is, less than one. Among farm products a commodity such as wheat (with few substitutes) would have a lower elasticity than a commodity such as wool which has many substitutes.

The values of the elasticities have significant policy implications. For example, for a highly price elastic commodity, an increase in price would result in a proportionately greater reduction in quantity demanded and farm revenues would decrease. A more realistic case for agricultural products would be the case of a price inelastic commodity. A given reduction in price (brought on, for example, by a shift in the supply function) would be accompanied by a proportionately lower increase in quantity demanded and total revenues would decrease.

3. Cross-Price Elasticity

When we speak of the demand schedule for commodity X as we did in the previous section, we are implicitly assuming that money income, tastes, and the nominal prices of related goods remain constant. In certain cases, however, the prices of related goods are interrelated with the price of commodity X. That is, if prices of related goods are allowed to vary, there will be a definite impact on the quantity demanded of commodity X.

Thus, our market demand function in this case is:

$$q_x = f(P_x, P_y)$$

where y is a related commodity. By defining the cross-price elasticity of demand we can characterize goods as either substitutes or complements. The cross-price elasticity of demand e_{xy} is defined as(7):

$$e_{xy} = \frac{\Delta q_x}{q_x} / \frac{\Delta P_y}{P_y} = \frac{\Delta q_x}{\Delta P_y} \cdot \frac{P_y}{q_x}$$

---

(7) Mathematically:

$$q_i = f(P_1, P_2, \ldots \ldots, P_n, Y)$$

$$e_{xy} = \frac{\partial q_i \; P_j}{\partial P_i \; q_i}, \quad i \neq j$$

It may be interpreted as the proportional change in the quantity of x demanded in response to a given change in the price of y. Commodities may be classified as substitutes if $e_{xy} > 0$ and complements if $e_{xy} < 0$.

Most empirical work has focused upon the substitutability of related commodities with substitutability (or relatedness) increasing as the cross-price elasticity increases. For example, George and King (1971) found the cross-elasticity of lettuce with respect to the price of carrots to be .000814 indicating that they are not closely related commodities. Wold (1953) found the cross-price elasticity coefficient of pork with respect to beef to be .14 and the coefficient of margarine with respect to butter to be .81. Thus, beef is a poor substitute for pork, while margarine and butter, as one might expect, are closely related and substitutable. As the price of butter rises we may expect consumers to purchase less butter and more margarine.

Substitution and Income Effects. Most empirical work focusing upon market demand uses the cross-elasticity approach to commodity classification in which the total effect of a price change is the criterion used to classify goods. Underlying this total effect are the substitution and income effects of price changes as they apply to individuals' preference functions. That is, a change in the nominal price of a commodity exerts two influences. The first is that a relative price change occurs, i.e., the terms at which a consumer exchanges one good for another. Second, a change in nominal price (nominal income remaining constant) means that relative income has changed, i.e., a consumer can buy a greater or smaller bundle of goods compared to before the price change. For example, a fall in the price of one good in the bundle effectively increases real income and we may expect that the consumer will buy either more of the good whose price decreased and/or more of other goods.

Translated into market terms, suppose we have two goods, wheat and corn. A decrease in the price of wheat (nominal money income and all other prices remaining constant) will augment the quantity demanded of wheat as consumers substitute it for corn. Simultaneously, the increase in real income may augment both wheat and corn purchases. In fact if the income effect was greater than the substitution effect it would appear that wheat and corn are complementary goods. An estimated cross-elasticity coefficient might even be negative -- indicating complementarity when in fact this is not the real case. Wheat and corn may well be weak substitutes, but the income effect outweighed the substitution effect. The total change can go either way. Generally, however, in the case of strong substitutes, the substitution effect will dominate. In the case of strong complements, the income effect will obviously dominate.

4. Income Elasticity of Demand

In the previous section we relaxed the assumption that the nominal prices of commodities related to X were constant. Analogously, in this section, we are relaxing the assumption of constant money income and allowing income to vary, since for many commodities a change in income will influence quantities purchased.

Assuming that our simplified market demand function is

$$q_x = f(P_x, Y)$$

we can define the income elasticity of demand e_y as (8):

$$e_y = \frac{\Delta q_x}{q_x} / \frac{\Delta Y}{Y} = \frac{\Delta q_x}{\Delta Y} \cdot \frac{Y}{q}$$

It may be interpreted as the proportional change in the quantity demand of X in response to a given change in real money income. Generally, if income elasticity is low (usually less than one), quantity demanded is not very responsive to income changes while if $e_y > 1$ quantity demanded is more responsive.

Empirically, Wold (1953) found the estimated income elasticity of meat to be .35 indicating that for a given increase in income there is a less than proportional increase in meat purchases. On the other hand, tobacco pruchases were very responsive to income changes.

The existence of inferior goods has been documented by estimated income elasticities. Wold (1953) found the income elasticities of flour and margarine to be -.36 and -.20 respectively indicating that as income rises the purchases of these two commodities actually decrease. George and King (1971) also found negative income elasticities for both commodities.

George and King found an income elasticity for all food items of .176 confirming that food is a necessity and that food purchases on the whole are relatively unresponssive to income changes.

We can summarize our description of the three types of elasticities by noting their interrelationship as follows:
For a given market demand function for one commodity,

$$q_1 = f(P_1, P_2, \ldots\ldots, P_n, Y)$$

We can write the direct price elasticity of demand as the sum of cross-price elasticities and its income elasticity(9).

---

(8) Mathematically: $q_1 = f(P_1, P_2, \ldots\ldots, P_y)$
and the income elasticity for the i^{th} commodity is $e_{iy} = \frac{\partial q_i}{\partial Y} \cdot \frac{Y}{q_i}$

(9) See Ferguson (1969), p. 45-46.

That is,

$$e_{11} = \sum_{i=2}^{n} e_{1i} + e_{1y} \qquad \text{for } i \neq 1;$$

or

$$\frac{\partial q_1}{\partial P_1}\frac{P_1}{q_1} = \sum_{i=2}^{n} \frac{\partial q_1}{\partial P_i}\frac{P_i}{q_1} + \frac{\partial q_1}{\partial Y}\frac{Y}{q_1} \qquad \text{for } i \neq 1.$$

C. STABILITY BENEFITS

Let us refer back to the discussion of Adams' QP model of California agruculture in VII, B. The maximand of the Adams' model constituted a quantitative measure of toal revenue to two groups: producers who maximize returns to land and management (producers' surplus (PS)) and consumers (defined as total value of the objective function minus net returns to producers, or consumers' surplus (CS)). The maximand, net social payoff (or net social benefit) equaled the sum of PS and CS.

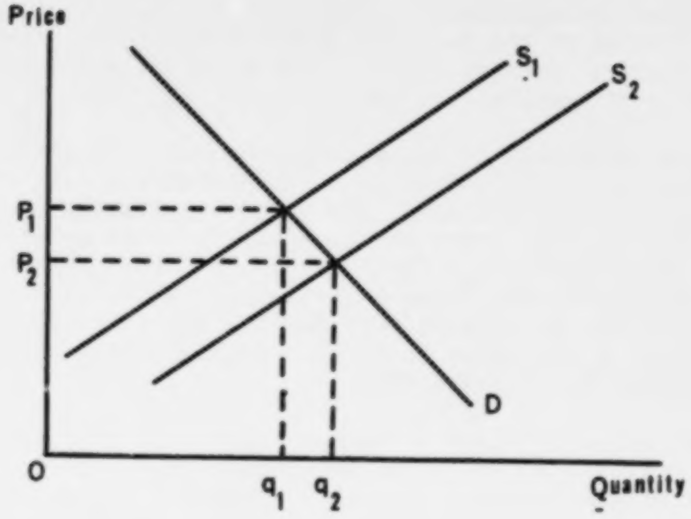
This maximand turned out to be particularly useful in analyzing the policy implications of energy constraints. Both theoretically and impirically, the impact of energy shortages was not shared equally by producers and consumers. That is, any given shortage would produce gainers and losers, irrespective of the change in net social welfare. Thus, Adams found that a significant shortage of fertilizer would reduce net social welfare, although the burden was distributed such that CS was relatively unchanged and PS was reduced. On the other hand, the impact of total energy shortages was to reduce CS and increase PS.

In this section we will look in more detail at the concepts of CS and PS, keeping in mind the application of these terms to the problem of air pollution damage in agriculture. The first assumption we must make is that the sum of CS and PS is an adequate measure of social welfare. This assumption has been the subject of extensive controversy in economic literature, but the fact remains that we have no better measures.

Before proceeding we can also clarify what we mean by stability benefits and further elucidate the terms CS and PS(10). First, given a typical negatively sloping market demand curve and a positively sloping market supply curve, it is clear that either shifts in supply (because of the influences of changes in factor costs, technology, weather, air pollution, water pollution, etc.) or demand (due to changes in consumer tastes, for example) will cause price fluctuations. The situation is illustrated in Figures 1 and 2. In Figure 1 an outward shift in supply from S_1 to S_2 would reduce price from P_1 to P_2. Alternatively, a reduction in supply would increase price. In Figure 2 a shift in demand from D_1 to D_2 would result in a change in equilibrium price (P_1 to P_2). Alternatively, if demand shifted downward price would decrease. It is easy to imagine that supply and/or demand instability would lead to considerable price instability.

---

(10) There is a large literature on the subject of price stabilization, most of it pertaining to international commodity price fluctuations. Massell (1969) synthesizes the pioneering work of Waugh (1944) on consumers' surplus and Oi (1961) on producers' surplus. Among numerous other pieces of research pertinent to stability are Turnovsky (1974), Bieri and Schmitz (1974), Samuelson (1972), Newbery (1976), and Subotnik and Houck (1976).


Price
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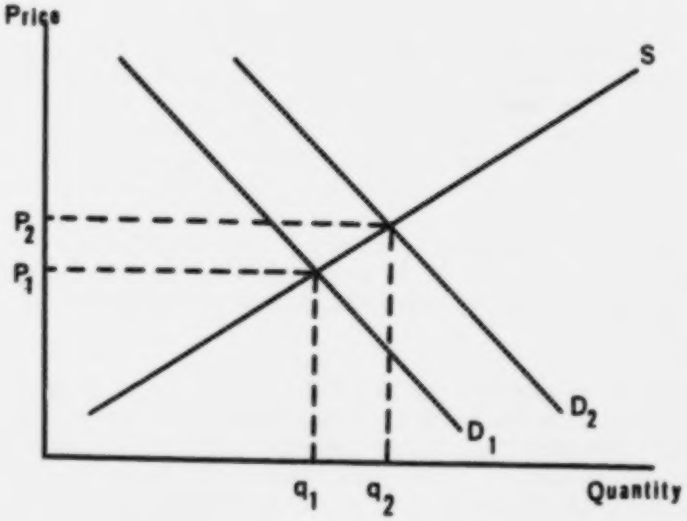
Quantity

Figure 1. Price change attributable to shift in supply.


Price
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D
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$_1$
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Quantity

Figure 2. Price change attributable to shift in consumer demand.

Now, following the Massell (1969, p. 285-287) synthesis of the work of Waugh (1944) and Oi (1961) on CS and PS respectively, we present Figures 3 and 4 in which P_1 and P_2 are equally likely prices faced by consumers and P_3 is an alternative (stable) price that obtains with certainty.

In Figure 3, CS may be defined as follows(11):

$$CS = \left[\begin{array}{ll} a + b + c + d + f & \text{if } P = P_1 \\ f & \text{if } P = P_2 \end{array} \right.$$

The expected value of CS is given by:

$$E\ (CS) = f + .5\ (a + b + c + d)$$

Under the stable price regime (P_3), expected CS is:

$$E\ (CS) = a + b + f$$

At the stabilized price, $P = P_3$, consumers lose an amount equal to $c + d$ compared to the prestabilization price $P = P_1$. Conversely, when $P = P_3$, consumers gain an amount equal to $a + b$ compared to the prestabilization price $P = P_2$. Since $c + d > a + b$, stabilization leads to a net loss in consumers' surplus(12).

Figure 4 represnets the situation under demand instability, Producers are confronted with two equally likely prices, P_1 and P_2, and a third price P_3 that obtains with certainty. Thus,

$$PS = \left[\begin{array}{ll} a + b + c + d + f & \text{if } P = P_2 \\ f & \text{if } P = P_1 \end{array} \right.$$

The expected value of PS is:

$$E\ (PS) = f + .5\ (a + b + c + d)$$

and at the stable price P_3,

$$E\ (PS) = a + b + f$$

---

(11) CS may be defined as the difference between the total area under a demand curve and the area representing expenditure by the consumer. For any combination (P_1, q_1),

$$CS = \int_0^{q1} f\ (q)\ dq - P_1 q_1$$

(12) Note that the source of instability is supply. It must also be assumed that the demand curve is negatively sloped and the marginal utility of money is constant with respect to price changes.

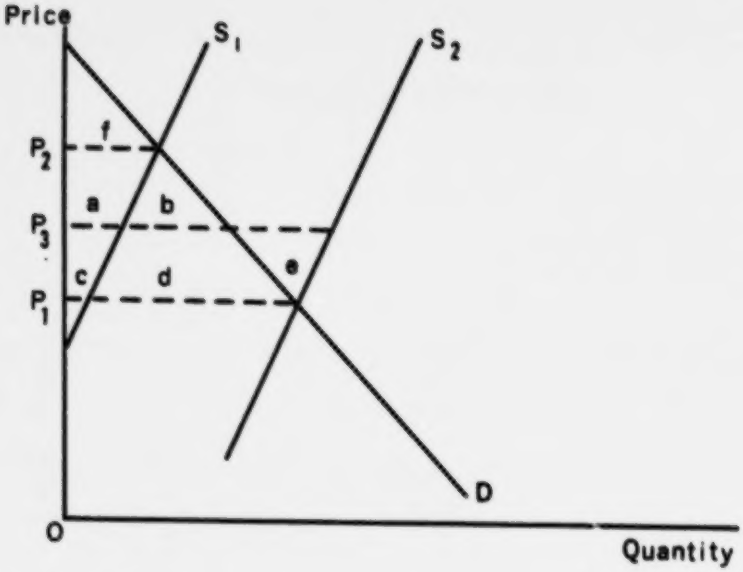

Figure 3. Effects of price stabilization on consumer surplus.

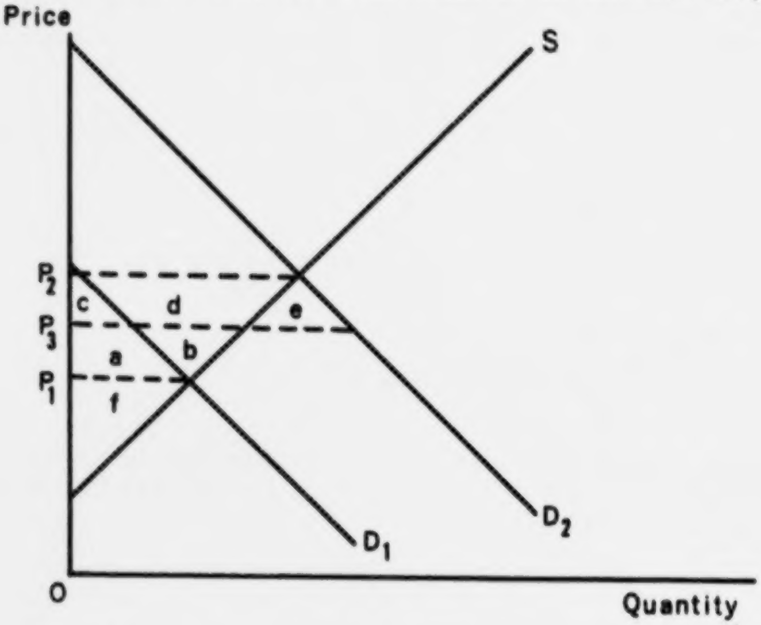

Figure 4. Effects of price stabilization on producer surplus.

Compared to the prestabilization price, $P = P_2$, producers lose an amount equal to c + d when $P = P_3$. However, compared to the prestabilization price $P = P_1$, producers gain an amount equal to a + b when $P = P_3$. Since $c + d > a + b$, producers' surplus is reduced under price stabilization with the amount of loss being equal to $1/2\ (c + d - a - b)$(13).

The discussion thus far provides a framework within which the generalizations that follow may be understood. Massell (1969) has shown that: (1) Producers gain from price stability if the source of instability is in supply; consumers, in contrast, lose from price stability if the source is supply; (2) Consumers gain from price stability if the source of instability is shifts in demand; producers lose in this case(14); (3) When demand and supply are random variables (as in the real world), the gains to each group depend upon the relative sizes of the variances of demand and supply and the slopes of the demand and supply functions. From the producers' perspective, both the likelihood and magnitude of gain from price stability are increasing functions of variance of supply and the steepness of the supply curve.

The Waugh-Oi-Massell work is based upon certain knowledge of prices. Turnovsky (1974) introduces two alternative models of price expectations for producers. That is, producers are assumed to make decisions based upon their expectations of prices. He concludes that producers gain from stabilization of supply regardless of how they form their expectations. If risk averse behavior is specified, the desirability of stabilization will be even greater(15).

Extending this analysis to the distributional effects of price stabilization (given supply side instability) among producers, a single producer will gain more from stability the steeper his supply curve relative to industry supply and the greater his variance in supply relative to industry supply.

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(13) In Figure 4, the source of instability is demand. Furthermore, it must be assumed that the supply curve is positively sloped and the marginal utility of money remains constant.

(14) We are ignoring the basic welfare question of whether the gainers (producers in (1) and consumers in (2)) can compensate the losers, leaving both parties better off.

(15) A subject of considerable importance is where, in a range of prices, price should be stabilized. In Figure 3 and 4, price was stabilized at the mean. However, Hazell and Scandizzo (1975) found that when risk enters market supply in a multiplicative way, social welfare may be increased by having an optimal market distortion involving a higher average price and lower expected supply as compared to a competitive market equilibrium price. The policy mechanisms necessary to obtain the distortion would probably include a combination quota and price stabilization scheme.

Conceptualization of the Impact of Air Pollution. Using the concepts discussed in C and assuming a constant technology, we might envision the scenario that follows(16). Suppose that in a given region, air pollution damage has reduced crop yields by some significant percentage. Furthermore, the region is subject ot increasing urbanization so that farmers have only had limited possibilities of expanding acreage to offset yield deficiencies. Thus, in general we might expect that market supplies are significantly below what they would be in the absence of pollution. Furthermore, given inelastic demand for agricultural commodities (see earlier subscetions in VIII), it is conceivable that pollution damage has actually increased farm revenues by limiting supply. This would be analogous to any other supply limitation program designed to increase prices and returns. Such programs include "green drop", acreage limitation, amrketing quotas, etc.

Now, suppose that because of air pollution standards set by the EPA or by local or regional air pollution districts, yields increase leading to increased commodity supplies(17). Again, given inelastic demand, we would expect farmers' revenues to decrease.

In Figure 5, due to increased yields induced by a reduction in air pollutant concentrations, supply has shifted from S_1 to S_2 and price has fallen from P_1 to P_2. Given the steeply sloped demand curve in the figure, the total revenue rectangle under the new price-quantity combination (d P_2 0 q_2) is clearly smaller than the pre-pollution standard combination (c P_1 0 q_1).

If we place this discussion in the context of the distributional impact of the supply shift we find that the shift from S_1 to S_2 has increased CS by area e + f + g. Producers' surplus changed by area (h + i) - g. As shown in Figure 5, PS is reduced. Social benefit increases by area e + f + h + i.

Thus, society gains by reducing air pollutant concentrations in agriculture, although the change has produced gainers (consumers) and losers (producers). This suggests the application of a very important concept in welfare economics, that of compensation. In this case the possibility exists of having the gainers compensate the losers for losses suffered in a socially beneficial change. The question of whether or not to compensate,

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(16) This scenario, for the most part, parallels (but in the opposite direction) what might occur due to a shift in the supply function induced by the innovation of new technology. For a specific example see Akino and Hayami (1975) in which the social returns to rice breeding research are estimated.

(17) Yields could also increase substantially due to technological improvements, particularly in pollution abatement equipment and pollution-resistant plants.

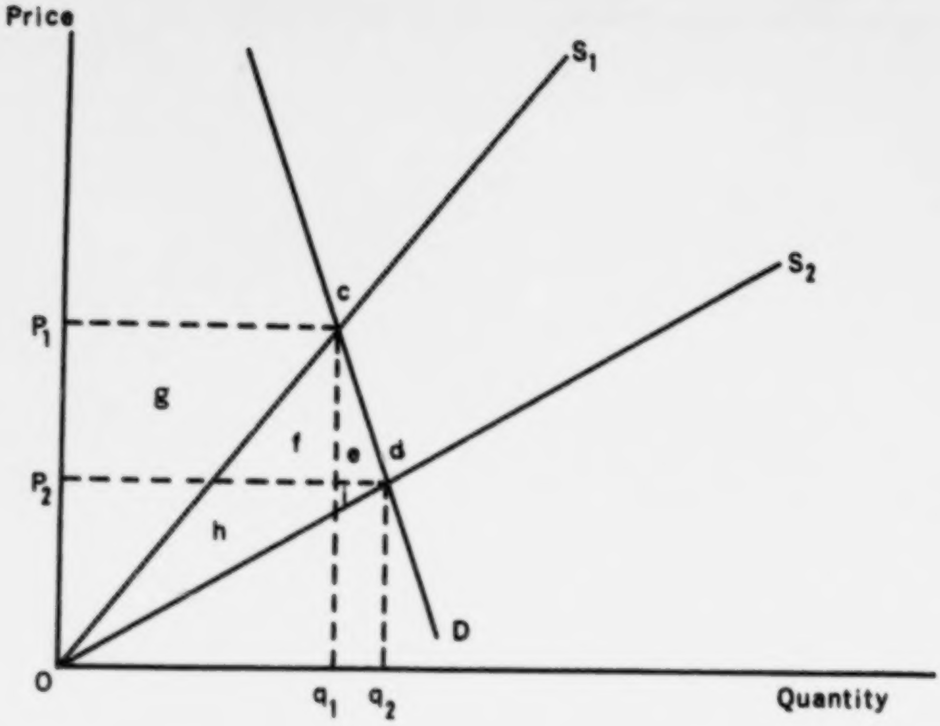
Price
S1
S2
c
P1
g
f
e
d
P2
i
h
D
O
q1
q2
Quantity

Figure 5. Welfare effects of a shift in market supply.

and the amount of compensation are political decisions, but theoretically it can be shown that the gainers could compensate the losers leaving both parties better off and leaving social benefit unchanged.

The same principle would apply if pollution control measures reduced the variation in supply schedule faced by the consumer.

REFERENCES - SECTION V-A

Abd El Rahman, H. A. and J. F. Bierhuizen. 1959. The effect of temperature and water supply on growth, transpiration and water requirement of tomato under controlled conditions. Meded. Landb. Hoogesch., Wageningen 59:1-13.

Allison, F. E., E. M. Roller and W. A. Raney. 1958. Relationship between evapotranspiration and yields of crops grown in lysimeters receiving natural rainfall. Agronomy J. 50:506-511.

Anonymous. 1965. Estimates of crop losses and disease-control costs in California. Univ. of Calif. Agric. Exp. Sta. and Agric. Exten. Service, Berkeley.

Anonymous. 1965. Agric. Res. Ser., U.S. Dept. Agric. Handbook No. 291.

Anonymous. 1957. Soil, Yearbook of Agriculture. U.S. Dept. of Agric., Washington.

Arkley, R. J. 1963. Relationships between plant growth and transpiration. Hilgardia 34:559-594.

Arnold, C. Y. 1959. The determination of the significance of the base temperature in a linear heat unit system. Proc. Amer. Soc. Hort. Sci. 74:430-445.

Arnon, I. 1972. Crop production in dry regions. Vol. I. Background and principles. Nicholas Polunin, ed. Leonard Hill, London.

Ashton, F. M. 1956. Effects of a series of cycles of alternating low and high soil water contents on the rate of apparent photosynthesis in sugar cane. Plant Physiol. 31:266-274.

Aspinall, D. and L. G. Paleg. 1964. Effects of day length and light intensity on growth of barley. Aust. J. Biol. Sci. 17:807-822.

Baier, W. 1973. Crop-weather analysis model: Review and model development. J. Appl. Meteorol. 12:937-947.

Baier, W. and G. W. Robertson. 1968. The performance of soil moisture estimates as compared with direct use of climatological data for estimating crop yields. Agric. Meteorol. 5:17-31.

Baier, W. and G. W. Robertson. 1966. A new versatile soil moisture budget. Can. J. Plant Sci. 47:299-316.

Begg, J. E. and N. C. Turner. 1976. Crop water deficits. Advan. Agron. 28:161-217.

Biddiscombe, E. F., P. G. Osanne, N. J. Barrow and J. Keay. 1969. A comparison of growth rates and phosphorus distribution in a range of pasture species. Aust. J. Agric. Res. 20:1023-1033.

Bierhuizen, J. F. 1961. Plant growth and soil moisture relationships. In: Plant-water relationships in arid and semi-arid conditions. p. 309-315. Unesco, Paris.

Bjorkman, O. B. Marshall, M. Nobs, W. Ward, F. Nicholson and H. Mooney. 1974. An analysis of the temperature dependence of growth under controlled conditions. Carnegie Inst. Year Book 73:757-767.

Black, J. N. 1955. The interaction of light and temperature in determining the growth rate of subterranean clover (Trifolium subterraneum L.) Aust. J. Biol. Sci. 8:330-343.

Blackman, G. E. 1961. Responses to environmental factors by plants in the vegetative phase. In: Growth in living systems. M. S. Zarrow, ed. Basic Books, Inc. New York. p. 525-556.

Blackman, G. E. and J. N. Black. 1959a. Physiological and ecological studies in the analysis of plant environment. XI. A further assessment of the influence of shading on the growth of different speices in the vegetative phase. Ann. Bot. 23:51-63.

Blackman, G. E. and J. N. Black. 1959b. Physiological and ecological studies in the analysis of plant environment. XII. The role of the light factor in limiting growth. Ann. Bot. 23:131-145.

Blackman, G. E. and G. L. Wilson. 1954. Physiological and ecological studies in the analysis of plant environment. IX. Adaptive changes in the vegetative growth and development of Helianthus annuus induced by an alternation of light intensity. Ann. Bot. 18:71.

Blackman, G. E. and G. L. Wilson. 1951. Physiological and ecological studies in the analysis of plant environment. VI. The constancy for different species of a logarithmic relationship between net assimilation rate and light intensity and its ecological significance. Ann. Bot. 15:63.

Blaney, H. F. and W. D. Criddle. 1962. Determining consumption use and irrigation water requirements. U.S. Dept. Agric. Tech. Bull.

Bohning, R. H. and C. A. Burnside. 1956. The effect of light intensity on rate of apparent photosynthesis in leaves of sun and shade plants. Amer. J. Bot. 43:557-561.

Boyer, J. S. 1971. Recovery of photosynthesis in sunflower after a period of low leaf water potential. Plant Physiol. 47:816-820.

Boyer, J. S. 1970. Leaf enlargement and metabolic rates in corn, soybean, and sunflower at various leaf water potentials. Plant Physiol. 46:233-235.

Boyer, J. S. and H. G. McPherson. 1975. Physiology of water deficits in cereal crops. Advan. Agron. 27:1-23.

Brenchley, W. E. 1920. On the relations between growth and the environmental conditions of temperature and bright sunshine. Ann. Appl. Biol. 6:211-244.

Brix, H. 1962. The effect of water stress on the rates of photosynthesis and respiration in tomato plant and loblolly pine seedlings. Physiol. Plant. 15:10-20.

Calvert, A. 1964. The effects of air temperature on growth of young tomato plants in natural light conditions. J. Hort. Sci. 39:194-211.

Camus, G. C. and F. W. Went. 1952. The thermoperiodicity of three varieties of Nicotiana tobacum. Amer. J. Bot. 39:521-528.

Chang, Jen-hu. 1968. Climate and agriculture: An ecological survey. Aldine Publishing Co., Chicago.

Chang, Jen-hu, R. B. Cambell and F. E. Robinson. 1963. On the relationship between water and sugar cane yield in Hawaii. Agron. J. 55:450-453.

Chapman, H. W., L. S. Gleason and W. E. Loomis. 1954. The carbon dioxide content of field air. Plant Physiol. 29:500-503.

Chapman, H. W. and W. E. Loomis. 1953. Photosynthesis in the potato under field conditions. Plant Physiol. 28:703-716.

Cole, J. S. 1938. Correlations between annual precipitation and yield of spring wheat in the Great Plains. U.S. Dept. Agric., Tech. Bull No. 636.

Cowan, I. R. 1965. Transport of water in the soil-plant-atmosphere system. J. Appl. Ecol. 2:221-239.

Cramer, H. H. 1967. Plant protection and world crop production. Bayer Pflanzenschuts, Leverkusen.

Dale, R. F. 1968. The climatology of soil moisture, evaporation, and non-moisture stress days for corn in Iowa. Agric. Meteorol. 5:111-128.

Decker, J. P., W. G. Gaylor and F. D. Cole. 1962. Measuring transpiration of undisturbed tamarisk shrubs. Plant Physiol. 37:393-397.

Deneke, H. 1931. Uber den Einfluss bewegter Luft auf die Kohlensaure-assimilation. Jb. Wiss. Bot. 74:1.

Dewan, M. L. and J. Famouri. 1964. The soils of Iran. F.A.O. of the United Nations, Rome.

De Wit, C. T. 1958. Transpiration and crop yields. Inst. voor Biol. en Scheikundig Onderzoek van Landbouwgewassen, Wageningen, Mededeling, No. 59.

Dolan, D. D. 1972. Temperature, photoperiod, and light intensity effects on growth of *Pisum sativum*. Crop Sci. 12:60-62.

Dorland, R. E. and F. W. Went. 1947. Plant growth under controlled conditions, Vii. Growth and fruiting of the chili pepper (*Capsicum annuum*). Amer. J. Bot. 34:393-401.

Downey, L. A. 1971. Effect of gypsum and drought stress on maize (*Zea mays* L.). I. Growth, light absorption and yield. Agron. J. 63:569-572.

Dyer, A. J. 1961. Measurements of evaporation and heat transfer in the lower atmosphere by an automatic eddy-correlation technique. Quart. J. Roy. Meteorol. Soc. 87:401-412.

Evans, L. T. (ed.). 1963. Environmental control of plant growth. Academic Press. New York.

Evans, L. T. and I. F. Wardlow. 1976. Aspects of the comparative physiology of grain yield in cereals. Advan. Agron. 28:301-359.

Erikson, R. O. 1959. Integration of plant growth processes. Amer. Nat. 93:225-235.

Eze, J. M. O. 1973. The vegetative growth of *Helianthus annuus* and *Phaseolus vulgaris* as affected by seasonal factors in Freetown, Sierra Leone. Ann. Bot. 37:315-329.

Ferguson, J. H. A. 1958. Empirical estimation of thermoreaction curves for rate of development. Euphytica 7:140-146.

Fibras, F. 1931. Die Wirkung des Windes auf die Transpiration. Bericht Deut. Bot. Ges. 49:443-452.

Fischer, R. A. 1975. Yield potential in spring wheat and the effects of shading. Crop Sci. 15:609-613.

Fischer, R. A. 1973. The effect of water stress at various stages of development on yield processes in wheat. In: Plant response to climatic factors. R. O. Slatyer, ed. p. 233-240. Unesco, Paris.

Fischer, R. A. and R. M. Hagen. 1965. Plant water relations, irrigation management and crop yield. Expt. Agric. 1:161-177.

Ford, M. A. and G. N. Thorne. 1975. Effects of variation in temperature and light intensity at different times on growth and yield of spring wheat. Ann. Appl. Biol. 80:283-299.

Gaastra, P. 1962. Photosynthesis of leaves and field crops. Netherlands J. Agric. Sci. 10:311-324.

Gaastra, P. 1959. Photosynthesis of crop plants as influenced by light, carbon dioxide, temperature, and stomatal diffusion resistance. Meded. Landb. Hoogesch., Wageningen 59:1-68.

Gardner, W. R. 1961. Factors governing the pattern of water utilization in a plant root zone. In: Plant-water relationships in arid and semi-arid conditions. p. 93-97. Unesco, Paris.

Gifford, R. M., P. M. Bremner and D. B. Jones. 1973. Assessing photosynthetic limitation to grain yield in a field crop. Aust. J. Agric. Res. 24:297-307.

Gilmore, E. C. Jr., and J. S. Rogers. 1958. Heat units as a method of measuring maturity in corn. Agron. J. 50:611-615.

Hagan, R. M. 1957. Water-soil-plant relations. Calif. Agric. 11(4):9-12.

Hartsema, A. M. 1961. Influence of temperatures on flower formation and flowering of bulbous and tuberous plants. In: Handbuch der Pflanzenphysiologie. W. Ruhland, ed., Vol. XVI, p. 123-167.

Haun, J. R. 1973. Determination of wheat growth-environment relationships. Agron. J. 65:813-816.

Haun, J. R., A. J. Lewis,III, S. J. Tsao, R. A. Baumgardener and D. O. Ezell. 1972. Analysis of crop-environment relationships and elaboration of the temperature response in snap bean production. S. C. Agr. Exp. Sta. Tech. Bull. 1040.

Hesketh, J. D. 1963. Limitations to photosynthesis responsible for differences among species. Crop Sci. 3:493-496.

Hesketh, J. D. and D. Baker. 1967. Light and carbon assimilation by plant communities. Crop Sci. 7:285-293.

Hesse, W. 1954. Der Einfluss meteorologischer Faktoren auf die Transpiration der Phefferminze (Mentha piperita L.). Angewandte Meteorol. 2:14-18.

Hodgson, G. L. 1967. Physiological and ecological studies in the analysis of the effects of seasonal variations in light energy and temperature on the growth of Helianthus annuus and Vicia faba in the vegetative phase. Ann. Bot. 31:291-308.

Hofstra, G. 1972. Response of soybeans to temperature under high light intensity. Can. J. Plant Sci. 52:535-543.

Hsiao, T. C. 1973. Plant responses to water stress. Ann. Rev. Plant Physiol. 24:519-570.

Huda, A. K. S., B. P. Ghildyal and V. S. Tomar. 1976. Contribution of climatic variables in predicting maize yield under monsoon conditions. Agric. Meteorol. 17:33-47.

Hughes, H. D. and D. S. Metcalfe. 1972. Crop production. 3rd ed., Macmillan, New York.

Husain, L. and D. Aspinall. 1970. Water stress and apical morphogenesis in barley. Ann. Bot. 34:393-407.

Hussey, G. 1965. Growth and development in the young tomato. III. The effect of night and day temperatures on vegetative growth. J. Expt. Bot. 16:373-385.

Keay, J., E. F. Biddiscombe and P. G. Ozanne. 1970. The comparative rates of phosphate absorption by eight annual pasture species. Aust. J. Agric. Res. 21:33-44.

Kenaga, C. B. 1970 Principles of phytopathology. Balt Publishers, Lafayette, Indiana.

Kuchl, R. O., D. R. Buxton and R. E. Briggs. 1976. Application of time series analysis to investigate crop and environment relationships. Agron. J. 68:491-495.

Lemon, E. R. 1960. Photosynthesis under field conditions: II. An aerodynamic method for determining the turbulence carbon dioxide exchange between the atmosphere and a corn field. Agron. J. 52:697-703.

Lemon, E. R. 1963. Energy and water balance of plant communities. In: L. T. Evans (ed.), Environmental control of plant growth. Academic Press New York, p. 55-78.

Ludlow, M. M. and G. L. Wilson. 1971. Photosynthesis of tropical pasture plants. II. Temperature and illuminance history. Aust. J. Biol. Sci. 24:1065-1075.

Makkink, G. F. 1957. Examining the Penman formula. Netherlands J. Agric. Sci. 5:290-305.

McCree, H. J. and S. D. Davis. 1974. Effect of water stress and temperature on leaf size and on size and number of epidermal cells in grain sorghum. Crop Sci. 14:751-755.

Millar, C. E. 1955. Soil fertility. Wiley and Sons, New York; Chapman and Hall, London.

Millar, C. E., L. M. Turk, and H. D. Foth. 1966. Fundamentals of soil science. Wiley and Sons, Inc., New York, London, Sydney.

Milthorpe, F. L. 1961. The income and loss of water in arid and semi-arid zones. In: Plant-water relationships in arid and semiarid conditions. Unesco, Paris.

Milthorpe, F. L. and Moorby. 1974. An introduction to crop physiology. Cambridge Univ. Press, London.

Molga, M. 1962. Agricultural Meterorlogy. Warsaw.

Monteith, J. L. 1965. Light destribution and photosynthesis in field crops. Ann. Bot. 29:17-37.

Mooney, H. A. and W. D. Billings. 1961. Comparative physiological ecology of arctic and alpine populations of Oxyric digyna. Ecol. Monographs 31:1-29.

Newman, J. R., W. C. Cooper, W. Reuther, G. A. Cahoon and A. Peynado. 1967. Orange fruit maturity and net heat accumulations. In: Ground level climatology, R. H. Shaw, ed., Pub. No. 86. Amer. Assoc. Advan. Sci., Washington. p. 127-147.

Nicholls, P. B. and L. H. May. 1963. Studies on the growth of barley apex. I. Interrelationships between primordium formation, apex length and spikelet development. Aust. J. Biol. Sci. 16:561-571.

Nuttonson, M. Y. 1957. The role of bioclimatology in agriculture with special reference to the use of thermal and photothermal requirements of pure line varieties of plants as a biological indicator in ascertaining climatic analogues (Homoclines). Int. J. Bioclimatol. Biomet. 1:1-20.

Parker, N. W. 1946. Environment factors and their control in plant environments. Soil Sci. 62:109-119.

Pelton, W. L. 1967. The effect of a windbreak on wind travel, evaporation and wheat yield. Can. J. Plant Sci. 47:209-214.

Pengra, R. F. 1952. Estimating crop yields at seeding time in the Great Plains. Agron. J. 44:271-274.

Penman, H. L. 1948. Natural evaporation from open water bare soil, and grass. Proc. Roy. Soc. Ser. A., 193:120-145.

Pfadt, R. E. (ed.) 1971. Fundamentals of applied Entomology. 2nd ed., Macmillan, New York.

Phipps, R. H., R. J. Fulford and F. C. Crofts. 1975. Relationships between the production of forage maize and accumulated temperature, Ontario heat units and solar radiation. Agric. Meteorol. 14:385-397.

Pruitt, W. O. 1963. Application of several energy balance and aerodynamic evaporation equations under a wide range of stability. In: Final report, Investigation of energy and mass transfer near the ground including influences of the soil-plant atmosphere system. Univ. of California, Davis, CA.

Raeside, J. D. 1962. Society, town planning, and the soil map. Transactions of joint meetings of commissions IV. and International Society of Soil Science. p. 854-858.

Rajan, A. K., B. Betteridge and G. E. Blackman. 1973. Differences in the interacting effects of light and temperature on growth of four species in the vegetative phase. Ann. Bot. 37:278-316.

Robertson, G. W. 1953. Some agrometeorological problems in Canada. Monthly Pub. Can. Br. Roy, Met. Soc. 4(2):1-21.

Robertson, G. W. 1973. Development of a simplified agroclimatic procedures for assessing temperature effects on crop development. In: Plant response to climatic factors. R. O. Slatyer, ed., Unesco, Paris. p. 327-343.

Russel, J. E. 1950. Soil conditions and plant growth. Longman, Green and Co., New York.

Russell, R. S., D. A. Barber and P. Newbould. 1961. Nutritional relationships between crops and soil. Outlook on Agric. 3:103-110.

Russell, R. S. and P. Newbould. 1969. In: Root growth. Whittington, W. J. (ed.) Proc. 15th Easter Sch. Agric. Sci., Univ. Nottingham, Butterworths, London.

Sale, P. J. M. 1966. The response of summer lettuce to irrigation at different stages of growth. J. Hort. Sci. 41:43-52.

Salter, P. J. and J. E. Goode. 1967. Crop responses to water at different stages of growth. Commonwealth Agric. Bureaux, Farnhans Royal.

Schneider, G. W. and N. F. Childers. 1941. Influence of soil moisture on photosynthesis, respiration, and transpiration of apple leaves. Plant Pnysiol. 16:565-583.

Schwalen, H. C. and M .E. Wharton. 1930. Lettuce irrigation studies. Bull. Ariz. Agric. Expt. Sta. 133:457-517.

Sedgley, R. H., L. A. Seaton and W. R. Stern. 1973 A field method for determining soil water availability to crop. In: Plant response to climatic factors. R. O. Slatyer, ed., Unesco, Paris. p. 527-530.

Setlik, I. (ed.) 1970 Prediction and measurement of photosynthetic productivity. Wageningen, Pudoc.

Sibma, L. 1970 Relation between total radiation and yield of some field crops in the Netherlands. Neth. J. Agric. Sci. 18:125-131.

Silsbury, J. H. 1971 The effects of temperature and light energy on dry weight and leaf area changes in seedling plants of Lolium perenne L. Aust. J. Agric. Res. 22:177-187.

Slatyer, R. O. 1969 Physiological significance of interval water relations to crop yield. In: Physiological aspects of crop yield. The Amer. Soc. of Agron. and Crop Sci. Soc. of Amer. p. 53-88.

Stafelt, M. G. 1932 Der Einfluss des Windes auf die Kutikulare und stomatare Transpiration. Svensk. Bot. Tidsk. 26:45-69.

Stanfield, B., D. P. Ormrod and H. F. Fletcher. 1966 Response of peas to environment. II. Effect of temperature in controlled environment cabinets. Can. J. Plant Sci. 46:195-203.

Stanhill, G. 1961 A comparison of methods calculating potential evapotrnaspiration from climatic data. Israel J. Agric. Res. 11:159-171.

Stanhill, G. 1973 Simplified agroclimatic procedures for assessing the effect of water supply. In: Plant response to climatic factors. R. O. Slatyer (ed.) Unesco, Paris. p. 461-476.

Staple, W. J. and J. J. Lehane. 1954a Wheat yield and use of moisture on substations in southern Saskatchewan. Can. J. Agric. Sci. 34:460-468.

Staple, W. J. and J. J. Lehane. 1954b Weather conditions influencing wheat yields in tanks and field plots. Can. J. Agric. Sci. 34:552-564.

Stapley, J. H. and F. C. H. Gayner. 1969 World crop protection. Vol. 1. Pests and diseases. The chemical rubber company, Cleavland.

Steele, J. G. 1967 Soil survey interpretation and its use. Soil Bull. No. 8. F. A. O. of the United Nations, Rome.

Tamm, E. and G. Krysch. 1961 Zum Verlauf des CO_2-Gehaltes der Luft. Zeit im Bereich landwirtschafelicher Kulturphlanzenbetande. Z. Acker Pflanz. 112:253-377.

Tanner, C. B. 1967 Measurements of evapotranspiration. In: Irrigation of agricultural lands. R. M. Hagan, R. H. Haise and T. W. Edminster, eds. Agronomy series. Amer. Soc. Agron. Madison, Wisconsin. p. 534-573.

Tanner, C. B. and W. L. Pelton. 1960 Potential evapotranspiration estimates by the approximate energy balance method of Penman. J. Geophysical. Res. 65:3391-3413.

Taylor, S. A. 1952 Estimating the intergrated soil tension in the root zone of growing crops. Soil Sci. 73:331-339.

Taylor, S. A. 1964 Water conditions and flow in the soil-plant-atmosphere system. Amer. Soc. Agron. Spec. Pub. 5:81-107.

Thompson, L. M. 1962 An evaluation of weather factors in the production of wheat. J. Soil Water Conserv. 17:149-156.

Thompson, L. M. and F. R. Troeh. 1973 Soil and soil fertility. McGraw-Hill, New York.

Thorne, G. N. 1970 Use of controlled environments for studying the effects of climatic factors on growth and yield. In: Prediction and measurement of photosynthetic productivity. I. Setlik, ed., Wageningen, Pudoc. p. 399-404.

Thorne, G. N., M. A. Ford and D. J. Watson. 1968 Growth, development and yield of spring wheat in artificial climate. Ann. Bot. 32:425-446.

Thorne, G. N., D. J. Watson and M. A. Ford. 1967 Effect of temperature variation at different times on growth and yield of sugar beet and barley. Ann. Bot. 31:71-101.

Thornthwaite, C. W. 1948 An approach toward a rational classification of climate. Geographical Rev. 38:55-94.

Thornthwaite, C. W. and B. Holzman. 1939 The determination of evaporation from land and water surface. Monthly Weather Rev. 67:4-11.

Thornthwaite, C. W. and J. R. Mather. 1954 Climate in relation to crops. Met. Monogr. 2:1-10.

Turner, N. C. and J. E. Begg. 1973 Stomatal behavior and water status of maize, sorghum, and tobacco under field conditions. I. At high soil water potential. Plant Physiol. 51:31-36.

Veihmeyer, F. J. and A. H. Holland. 1949 Irrigation and cultivation of lettuce. Bull. Calif. Agric. Expt. Sta. 711.

Viglierchio, D. R. and F. W. Went. 1957 Plant growth under controlled conditions. XI. Growth and fruiting of Kentucky wonder bean (*Phaseolus vulgaris*). Amer. J. Bot. 44:449-453.

Visser, W. C. 1961 Soil moisture sampling as a basis for a detailed description of moisture utilization by crops. In: Plant-water relationships in arid and semi-arid conditions. Unesco, Paris. p. 33-41.

Voldeng, H. D. and G. E. Blackman. 1973 The influences seasonal changes in solar radiation and air temperature on the growth in the early vegetative phase of *Zea mays*. Ann. Bot. 37:553-563.

Waddington, J. 1973 Use of factor analysis to investigate relations between environmental variables and forage yield. Can. J. Plant Sci. 53:309-316.

Wadsworth, R. M. 1959 An optimum wind speed for plant growth. Ann. Bot. 23:195-199.

Waggoner, P. E., D. M. Moss and J. D. Hesketh. 1963 Radiation in the plant environment and photosynthesis. Agron. J. 55:36-38.

Walter, H. 1963 The water supply of desert plants. In: The water relations of plants. J. Rutter and F. H. Whitehead, eds., Oxford, Blackwell. p. 199-205.

Wang, J. Y. 1960 A critique of the heat unit approach to plant response studies. Ecology 41:785-790.

Warren Wilson, J. 1967 Effects of seasonal variation in radiation and temperature on net assimilation rate and growth rates in an arid climate. Ann. Bot. 31:41-57.

Watson, D. J., T. Motomatsu, K. Loach and G. F. J. Milfrod. 1972 Effects of shading and of seasonal differences in weather on the growth, sugar content and sugar yield of sugar beet crops. Ann. Appl. Biol. 71:159-185.

Watts, W. R. 1974 Leaf extension in *Zea mays* III. Field measurements of leaf extension in response to temperature and leaf water potential. J. Expt. Bot. 25:1085-1096.

Webster, J. M. 1972 Economic nematology. Academic Press, New York.

Went, F. W. 1948 Thermoperiodicity. In: Vernalization and photoperiodism. Lolsya, I. Chronica Botanica, Waltham, Mass. P. 145-157.

Went, F. W. 1956 The role of environment in plant growth. Amer. Scientist 44:378-398.

Went, F. W. 1957 The experimental control of plant growth. Ronald Press, New York.

Went, F. W. and L. O. Sheps. 1969 Environmental factors in regulation of growth and development: Ecological factors. In: Plant Physiology a Treatise. F. C. Steward, ed. Academic Press, New York. p. 299-406.

Whitehead, F. H. 1957 Wind as a factor in plant growth. In: Control of the plant environment. J. P. Hudson, ed., London: Butterworth Scientific Publications. p. 84-95.

Whiteman, P. C. and G. L. Wilson. 1965 The effects of water stress on the reproductive development of *Sorghum vulgare* Pers. Queensland Univ. Dept. Bot. 4:233-239.

Whyte, R. O. 1960 Crop production and environment. Faber and Faber, London.

Williams, G. D. V. 1969 Weather and prairie wheat production. Can. J. Agric. Econ. 17:99-109.

Wilson, W. J. and R. M. Wadsworth. 1958 The effect of wind speed on assimilation rate - a reassessment. Ann. Bot. 22:285-290.

Yoshino, M. M. 1974 Agricultural climatology in Japan. In: Agricultural meteorology of Japan. Yoshiaki, M. ed., University of Tokyo Press, Tokyo. p. 11-40.

REFERENCES - SECTION V-B

Adedipe, N. O., G. Hofstra and D. P. Ormrod. 1972 Effects of sulfur nutrition on phytotoxicity and growth responses of bean plants to ozone. Can. J. Bot. 50:1789-1793.

Applegate, H. G. and L. C. Durrant. 1969 Synergistic action of ozone-sulphur dioxide on peanuts. Environ. Sci. Tech. 3:759-760.

Brennan, E., I. Leone and R. H. Daines. 1962 Ammonia injury to apples and peaches in storage. Plant Dis. Reptr. 46:792-795.

Brennan, E., I. A. Leone and R. H. Daines. 1950 Fluorine toxicity in tomato as modified by alterations in the nitrogen, calcium and phosphorus nutrition of plants. Plant Physiol. 25:736-747.

Bennett, J. H., A. C. Hill, A. Soleimani and W. H. Edwards. 1975 Acute effects of combinations of sulfur dioxide and nitrogen dioxide on plants. Environ. Pollut. 9:127-132.

Brewer, R. F., F. B. Guillemet and R. K. Creveling. 1961 Influence of N-P-K fertilization on incidence and severity of oxidant injury to mangels and spinach. Soil Sci. 92:298-301.

Brewer, R. F., F. H. Sotherland, F. B. Guillemet and R. K. Creveling. 1960. Some effects of hydrogen fluoride gas on bearing navel orange trees. Amer. Soc. Hort. Sci. 76:208-214.

Brisley, H. R., C. R. Davis and J. A. Booth. 1959 Sulphur dioxide fumigation of cotton with special reference to its effect on yield. Agron. J. 51:77-80.

Chambers, L. A. 1968 Classification and extent of air pollution problems. In: Air Pollution. A. C. Stern, ed., Academic Press, New York, London.

Craker, L. E. 1971 Effects of mineral nutrients on ozone susceptibility of Lemna minor. Can. J. Bot. 49:1411-1414.

Darley, E. F. 1966 Studies on the effect of cement-kiln dust on vegetation. J. Air Pollu. Cont. Accoc. 16:145-150.

Davis, D. D. and S. H. Smith. 1974 Reduction of ozone-sensitivity of pinto bean by bean common mosaic virus. Phytopath. 64:383-385.

Davis, D. D. and F. A. Wood. 1973 The influence of environmental factors on the sensitivity of Virginia pine to ozone. Phytopath. 63:371-376.

De Ong, E. R. 1946 Injury to appricot leaves from fluorine deposit. Phytopath. 36:469-471.

Dochinger, L. S., F. W. Bender, F. O. Fox and W. W. Heck. 1970 Chlorotic dwarf of eastern white pine caused by ozone and sulfur dioxide interaction. Nature 225:476.

Dugger, W. M., O. C. Taylor, E. Cardiff and C. R. Thompson. 1962 Relationship between carbohydrate content and susceptibility of pinto bean plants to ozone damage. Amer. Soc. Hort. Sci. 81:304-314

Dugger, W. W. Jr., O. C. Taylor, W. H. Klein and W. Shropshir, Jr. 1963 Action spectrum of peroxyacetyl nitrate damage to bean plants. Nature 198:75-76.

Dunning, J. A. and W. W. Heck. 1973 Response of pinto bean and tobacco to ozone as conditioned by light intensity and/or humidity. Environ. Sci. Tech. 7:824-826.

Dunning, J. A., W. W. Heck and D. T. Tingey. 1974 Foliar sensitivity of pinto bean and soybean to ozone as affected by temperature, potassium nutrition and ozone dose. Water Air Soil Pollut. 3:305-311.

Engle, R. L. and W. H. Gabelman. 1967 The effect of low levels of ozone on pinto beans, Phaseolus vulgaris L. Amer. Soc. Hort. Sci. 91:304-309.

Glater, R. B., R. A. Solberg and F. M. Scott. 1962 A developmental study of the leaves of Nicotiana glutinosa as related to their smong-sensitivity. Amer. J. Bot. 49:954-970.

Hall, W. C., G. B. Truchelut, C. L. Leinweber and F. H. Herrero. 1957 Ethylene production by the cotton plant and its effects under experimental and field condition. Physiol. Plant. 10:306-317.

Heagle, A. S. and L. W. Key. 1973a Effect of ozone on the wheat stem rust fungus. Phytopath. 63:397-400.

Heagle, A. S. and L. W. Key. 1973b Effect of Pucinia graminis f. sp. tritica on ozone injury in wheat. Phytopath. 63:609-613.

Heagle, A. S., D. E. Body and G. E. Neely. 1974 Injury and yield responses of soybean to chronic doses of ozone and sulfur dioxide in the field. Phytopath. 64:132-136.

Heagle, A. S., D. E. Body and E. K. Pounds. 1972 Effect of ozone on yield of sweet corn. Phytopath. 62:683-687.

Heggestad, H. E. 1973 Photochemical air pollution injury to potato in the atlantic coastal states. Amer. Potato J. 50:315-328.

Heggestad, H. E. and J. T. Middleton. 1959 Ozone in high concentrations as cause of toabcco leaf injury. Sci. 129:208-210.

Heck, W. W. 1976 Plant and Microorganisms. In: Environmental health effects. Vol. 2. Ozone and other photochemical oxidants. Chapter 11. EPA-600/1-76-027 b. U.S. E.P.A. Office Res. Dev., Health Effects Res. Lab., Res. Triangle Park, N. C.

Heck, W. W. 1968 Factors influencing expression of oxidant damage to plants. Ann. Rev. Phytopath. 6:165-188.

Heck, W. W. and J. A. Dunning. 1967 The effects of ozone on tobacco and pinto bean as conditioned by several ecological factors. J. Air. Pollut. Cont. Assoc. 17:112-114.

Heck, W. W., J. A. Dunning and I. J. Hindawi. 1966 Ozone: Nonlinear relation of dose and injury in plants. Sci. 151:577-578.

Heck, W. W., J. A. Dunning and I. J. Hindawi. 1965 Interactions of environmental factors on the sensitivity of plants to air pollution. J. Air Pollut. Cont. Assoc. 15:511-515.

Heck, W. W. and D. T. Tingey. 1971 Ozone. Time-concentration model to predict acute foliar injury. In: H. M. Englund and W. T. Beery, eds. Proceedings of the second international clean air congress. Held at Washington, D. C., Dec. 6-11, 1970, New York: Academic Press. p. 249-255.

Hill, A. C., S. Hill, C. Lamb and T. W. Barrett. 1974 Sensitivity of native desert vegetation to SO_2 and SO_2 + NO_2. J. Air Pollut. Cont. Assoc. 24:153-157.

Hitchcock, A. E., P. W. Zimmerman and R. R. Coe. 1963 The effect of fluorides on Milo maize (Sorghum sp.). Contrib. Boyce Thompson Inst. 22:175-206.

Hitchcock, A. E., P. W. Zimmerman and R. R. Coe. 1962 Results of ten years' work (1951-1960) on the effect of fluorides on gladiolus. Contrib. Boyce Thompson Inst. Pl. Res. 21:303-344.

Hoffman, G. J., E. V. Maas and S. L. Rawlins. 1975 Salinity - Ozone interactive effects on alfalfa yield and water relations. J. Environ. Qual. 4:326-331.

Hoffman, G. J., E. V. Maas and S. L. Rawlins. 1973 Salinity-ozone interactive effects on yield and water relations of pinto bean. J. Environ. Qua. 2:148-152.

Jacobson, J. S. and A. C. Hill, eds. 1970 Recognition of air pollution injury to vegetation: A pictorial atlas. Air Pollut. Contrib. Assoc., Air pollut. Contrib. Admin., Inform. Rept. 1 A1-H3.

Jenson, Keith F. 1973 Response of nine forest tree species to chronic ozone fumigation. Plant Dis. Reptr. 57:914-917.

Juhren, M., W. Noble and F. W. Went. 1957 The standardization of *Poa annua* as an indicator of smog concentrations. I. Effects on temperature, photoperiod, and light intensity during growth of the test-plants. Plant Physiol. 32:576-586.

Kerr, E. D. and R. A. Reinert. 1968 The response of bean to ozone as related to infection by *Pseudomonas phaseolicola* (abstract). Phytopath. 58:1055.

Khantamian, H. N. O. Adedipe and D. P. Ormrod. 1973 Soil-plant-water aspects of ozone phototoxicity in tomato plants. Plant Soil 38:531-541.

Leone, I. A. and E. Brennan. 1972 Modification of sulfur dioxide injury to tobacco and tomato by varying nitrogen and sulfur nutrition. J. Air Pollut. Cont. Assoc. 22:544-547.

Leone, I. A. and E. Brennan. 1970 Ozone toxicity on tomato as modified by phosphorus nutrition. Phytopath. 60:1521-1524.

Leone, I. A., E. Brennan and R. H. Daines. 1966 Effect of nitrogen nutrition on the response of tobacco to ozone in the atmosphere. J. Air Pollut. Cont. Assoc. 16:191-196.

Lerman, S. L. and E. F. Darley. 1975 Particulates. In: Responses of plants to air pollution. J. B. Mudd and T. T. Kozlowski, eds. Academic press, New York, San Francisco, London. p. 141-158.

Linzon, S. N. 1965 Sulfur dioxide injury to trees in the vicinity of petroleum refineries. Forestry Chronicle 41:245-247.

Macdowall, F. D. H. 1965 Predisposition of tobacco to ozone damage. Can. J. Plant Sci. 45:1-12.

Macdowall, F. D. H. and A. F. W. Cole. 1971 Threshold and synergistic damage to tobacco by ozone and sulfur dioxide. Atmos. Environ. 5:553-559.

Magdycz, W. P. and W. J. Manning. 1973 *Botrytis cinerea* protects broad bean against visible ozone injury (abstract). Phytopath. 63:204.

Mandl, R. H., L. H. Weinstein and M. Keveny. 1975 Effects of hydrogen fluoride and sulfur dioxide alone and in combination on several species of plants. Environ. Pollut. 9:133-143.

Manning, W. J. 1975 Interactions between air pollutants and fungal, bacterial and viral plant pathogens. Environ. Pollut. 9:87-90.

Manning, W. J., W. A. Feder and I. Perkins. 1970 Ozone injury increases infection of geranium leaves by *Botrytis cinerea*. Phytopath. 60:669-670.

Manning, W. J., W. A. Feder, I. Perkins and M. Glickman. 1969 Ozone injury and infection of potato leaves by Botrytis cinerea. Plant Dis. Reptr. 53:691-693.

Manning, W. J., W. A. Feder and P. M. Vardaro. 1974 Suppression of oxidant injury by benomyl: Effects on yields of bean cultivars in the field. J. Environ. Qual. 3:1-3.

Matsushima, J. and R. F. Brewer. 1972 Influence of sulfur dioxide and hydrogen fluoride as a mix or reciprocal exposure on citrus growth and development. J. Air Pollut. Cont. Assoc. 22:710-713.

McCune, D. C. 1969 Floride criteria for vegetation reflect the diversity of the plant kingdom. Environ. Sci. Tech. 3:720-735.

McIlveen, W. D., R. A. Spotts and D. D. Davis. 1975 The influence of soil zinc on nodulation, mycorrhizae, and ozone-sensitivity of pinto bean. Phytopath. 65:645-647.

Means, Jr. W. E., and N. L. Lacasse. 1969 Relative sensitivity of twelve tree species to hydrogen chloride gas (abstract). Phytopath. 59:401.

Menser, H. A. and H. E. Heggestad. 1966 Ozone and sulphur dioxide synergism. Injury to tobacco plants. Sci. 153:424-425.

Middleton, J. T. 1961 Photochemical air pollution to plants. Ann. Rev. Plant Physiol. 12:431-448.

Middleton, J. T., A. S. Crafts, R. F. Brewer and O. C. Taylor. 1956 Plant damage by air pollution. Cal. Agric. 10(8):9-10.

Middleton, J. T. and A. O. Paulus. 1956 The identification and distribution of air pollutants through plant response. Arch. Ind. Health. 14: 526-532.

Miller, P. R., J. R. Parmeter, Jr., O. C. Taylor and E. A. Cardiff. 1963 Ozone injury to the foliage of Pinus ponderosa. Phytopath. 53:1072-1080.

Millican, A. A. 1976 A survey and assessment of air pollution damage to California vegetation, 1970 through 1974. State of California, Dept. of Food and Agriculture.

Millican, A. A. 1971 A survey and assessment of air pollution damage to California vegetation in 1970. California, Dept of Agriculture.

Mudd, J. B. and T. T. Kozlowski, eds. 1975 Physiological Ecology. A series of monographs, texts and treatises. Responses of plants to air pollution. Academic Press, New York.

Naegele, J. A. ed. 1973 Air pollution damage to vegetation. Adv. Chem. ser. 122. Amer. Chem. Soc., Washington, D. C.

Noble, W. M. 1955 Pattern of damage produced on vegetation by smog. Agric. Food Chem. 3:330-332.

Oertli, J. J. 1959 Effect of salinity on susceptibility of sunflower plants to smog. Soil Sci. 87:249-251.

Ormrod, D. P. and N. O. Adedipe. 1974 Protecting horticultural plants from atmospheric pollutants: A review. Hort. Sci. 9:108-111.

Ormrod, D. P., N. O. Adedipe and G. Hofstra. 1973 Ozone effects on growth of radish plants as influenced by nitrogen and phosphorus nutrition and by temperature. Plant Soil. 39:437-439.

Oshima, R. J. 1973 Effect of ozone on a commercial sweet corn variety. Plant Dis. Reptr. 57:719-723.

Oshima, R. J., O. C. Taylor, P. K. Braegelmann and D. W. Baldwin. 1975 Effect of ozone on the yield and plant biomass of a commercial variety of tomato. J. Environ. Qual. 4:463-464.

Otto, H. W. and R. H. Daines. 1969 Plant injury by air pollutants: Influence of humidity on stomatal apertures and plant response to ozone. Sci. 163:1209-1210.

Page, A. L., T. J. Ganje and M. S. Joshi. 1971 Lead quantities in plants, soil, and air near some major highways in southern California. Hilgardia 41. No. 1.

Pippen, E. L., A. L. Potter, V. G. Randall, K. C. Ng, F. W. Reutre III, A. I. Morgan, Jr. and R. J. Oshima. 1975 Effect of ozone fumigation on crop composition. J. Food Sci. 40:672-676.

Rhoads, A., J. Troiaw and E. Breunan. 1973 Ethylene gas as a cause of injury to easter lilies. Plant Dis. Reptr. 57:1023-1024.

Rich, S. and N. C. Turner. 1972 Importance of moisture on stomatal behavior of plants subjected to ozone. J. Air Pollut. Cont. Assoc. 22:718-721.

Richards, B. L., J. T. Middleton and W. B. Hewitt. 1958 Air pollution with relation to agronomic crops: V. Oxidant stipple to grape. Agron. J. 50:559-561.

Ryder, E. J. 1973 Selecting and breeding plants for increased resistance to air pollutants. In: Air pollution damage to vegetation. Naegele, J. A. ed. Adv. Chem. Ser. 122. Amer. Chem. Soc., Washington, D. C.

Seidman, G., I. J. Hindawi and W. W. Heck. 1965 Environmental conditions affecting the use of plants as indicators of air pollution. J. Air Pollut. Cont. Assoc. 15:168-170.

Shinohara, T., Y. Yamamoto, H. Kitano and M. Fukuda. 1974 Interactions of light and ozone injury in tobacco. Proc. Crop. Sci. Soc. Jap. 43: 433-438.

Shinohara, T., Y. Yamamoto, H. Kitano and M. Fukuda. 1973 Effects of temperature on ozone injury to tobacco. Proc. Crop Sci. Soc. Jap. 42:418-421.

Skelly, J. M., L. D. Moore and L. L. Stone. 1972 Symptom expression of eastern white pine located near a source of oxides of nitrogen and sulfur dioxide. Plant Dis. Reptr. 56:3-6.

Stolzy, L. H., O. C. Taylor, W. M. Dugger, Jr. and J. D. Mersereace. 1964 Physiological changes in and ozone susceptibility of the tomato plants after short periods of inadequate oxygen diffusion to the roots. Proc. Soil Sci Soc. Amer. 28:305-308.

Stolzy, L. H., O. C. Taylor, J. Letey and T. E. Szuszkiewicz. 1961 Influence of soil-oxygen diffusion rates on susceptibility of tomato plants to air-borne oxidants. Soil Sci. 91:151-155.

Taylor, O. C. 1974 Air pollutant effects influenced by plant-environmental interaction. In: Air pollution effects on plant growth. Dugger, M. ed. ACS symposium Ser. 3. Amer. Chem. Soc., Washington, D.C.

Taylor, O. C. 1973 Acute responses of plants to aerial pollutants. In: Air pollution damage to vegetation. J. A. Naegele, ed. Adv. Chem. Ser. 122, Amer. Chem. Soc., Washington, D. C.

Taylor, O. C. 1969 Importance of peroxyacetyl nitrate (PAN) as a phytotoxic air pollutant. J. Air Pollut. Cont. Assoc. 19:347-351.

Taylor, O. C., W. M. Dugger, Jr., E. A. Cardiff and E. F. Darley. 1961 Interaction of light and atmospheric photochemical products ("smog") within plants. Nature 192:814-816.

Taylor, O. C., E. R. Stephens, E. F. Darley and E. A. Cardiff. 1960 Effect of air-borne oxidants on leaves of pinto bean and petunia. Amer. Soc. Hort. Sci. 75:435-444.

Thomas, M. D. and G. R. Hill. 1937 Relation of sulfur dioxide in the atmosphere to photosynthesis and respiration of alfalfa. Plant Physiol. 12:309-383.

Thompson, C. R. and O. C. Taylor. 1969 Effects of air pollutants on growth, leaf drop, and yield of citrus trees. Environ. Sci. Tech. 3:934-940.

Ting, I. P. and W. M. Dugger, Jr. 1968 Factors affecting ozone sensitivity and susceptibility of cotton plants. J. Air Pollut. Cont. Assoc. 18: 810-813.

Tingey, D. T., W. W. Heck and R. A. Reinert. 1971 Effect of low concentrations of ozone and sulfur dioxide on foliage growth and yield of radish. Amer. Soc. Hort. Sci. 96:369-371.

Tingey, D. T. and R. A. Reinert. 1975 The effect of ozone and sulfur dioxide singly and in combination on plant growth. Environ. Pollut. 9:117-125.

Tingey, D. T., R. A. Reinert, J. A. Dunning and W. W. Heck. 1973 Foliar injury responses of eleven plant species to ozone/sulfur dioxide mixtures. Atmos. Environ. 7:201-208.

Tingey, D. T., R. A. Reinert, J. A. Dunning and W. W. Heck. 1971 Vegetation injury from the interaction of nitrogen dioxide and sulfur dioxide. Phytopath. 61:1506-1511.

Weinstein, L. H., D. C. McCune, A. L. Aluisio and P. Van Leuken. 1975 The effect of sulfur dioxide on the incidence and severity of bean rust and early blight of tomato. Environ. Pollut. 9:145-155.

White, K. L., A. C. Hill and J. H. Bennett. 1974 Synergistic inhibition of apparent photosynthesis rate of alfalfa by combinations of sulfur dioxide and nitrogen dioxide. Environ. Sci. Tech. 8:574-576.

Yardwood, C. E. and J. T. Middleton. 1954 Smog injury and rust infection. Plant Physiol. 29:393-395.

REFERENCES - SECTION V-C

Anonymous. 1965 Estimates of crop losses in California, 1963. Univ. of Calif. Agric. Expt. Sta. and Agric. Exten. Service, Berkeley.

Baier, W. 1973 Crop-weather analysis model: review and model development. J. Appl. Meteorol. 12:937-947.

Baier, W. 1967 Recent advancements in the use of climatic data for estimating soil moisture. Ann. Arid Zone 6(1):1-21.

Baier, W. and G. W. Robertson. 1968 The performance of soil moisture estimates as compared with direct use of climatological data for estimating crop yields. Agric. Meteorol. 5:17-31.

Baier, W. and G. W. Robertson. 1966 A new versatile soil moisture budget. Can. J. Plant Sci. 47:299-316.

Benedict, H. M., C. J. Miller and J. S. Smith. 1973 Assessment of economic impact of air pollutants on vegetation in the United States: 1969 and 1971. Final Report, SRI Project LSU-1503. Stanford Research Institute, Menlo Park, California. 96pp.

Benedict, H. M., C. J. Miller and R. E. Olson. 1971 Economic impact of air pollutants on plants in the United States. Final Report, SRI project LSD-1056. Stanford Research Institute, Menlo Park, California. 77pp.

Brandt, C. S. and W. W. Heck. 1968 Effects of air pollutants on vegetation. In: Air Pollution Volume I. A. C. Stern (ed.). p. 401-443. Academic Press, New York.

Brisley, H. R., C. R. Davis and J. A. Booth. 1959 Sulphur dioxide fumigation of cotton with special reference to its effect on yield. Agron. J. 51:77-80.

Brisley, H. R. and W. W. Jones. 1950 Sulphur dioxide fumigation of wheat with special reference to its effect on yield. Plant Physiol. 25:666-681.

Buck, S. F. 1961 The use of rainfall, temperature, and actual transpiration in some crop-weather investigations. J. Agric. Dci. 57:355-365.

Dale, R. F. and R. H. Shaw. 1965 The climatology of soil moisture, atmospheric evaporative demand, and resulting moisture stress days for corn at Ames, Iowa. J. Appl. Meteorol. 4:661-669.

Das, J. C. and M. L. Madnani. 1971 Forecasting the yield of principal crops in India on the basis of weather: paddy-rice (Koukan and Madhya Maharashtra). Agrimet No. 1, Part 1, India Meteorol. Dept., Poona, p. 1-15.

Dermine, P. and H. R. Klinck. 1966 The value of standard weather data in yield-climate studies of two oat varieties. Can. J. Plant Sci. 46:27-34.

Earley, E. B., R. J. Miller, G. L. Reichert, R. H. Hageman and R. D. Seif. 1966 Effect of shade on maize production under field conditions. Crop Sci. 6:1-7.

Feliciano, A. 1971 Survey and assessment of air pollution damage to vegetation in New Jersey. New Brunswick, New Jersey. Co-operative Extension Service, CAES, Rutgers, The State Univ.

Fisher, R. A. 1924 The influence of rainfall on the yield of wheat at Rothamstad. Phil. Brans. Ser. B. 213:89-142.

Gangopadhyaya, M. and R. P. Sarker. 1965 Influence of rainfall distribution on the yield of wheat crop. Agric. Meteorol. 2:331-350.

Haise, H. R. and R. M. Hagan. 1967 Soil, plant and evaporative measurements as criteria for scheduling irrigation. Agronomy 11:577-597.

Haun, J. R. 1973 Determination of wheat growth environment relationships. Agron. J. 65:813-816.

Heagle, A. S., D. E. Body and W. W. Heck. 1973 An open-top field chamber to assess the impact of air pollution on plants. J. Environ. Qual. 3:365-368.

Heck, W. W. 1976 Plant and Microorganisms. In: Environmental Health Effects., Vol. 2, Ozone and other photochemical oxidants. Chapter 11. EPA-600/1-76-0276. U.S. E.P.A. Office Res. Dev., Health Effects Res. Lab., Res. Triangle Park, N. C.

Heck, W. W., J. A. Dunning and I. J. Hindawi. 1966 Ozone: Non-linear relation of dose injury in plants. Sci. 151:577-578.

Heck, W. W. and D. T. Tingey. 1971 Time-concentration model to predict acute foliar injury. In: Proceedings of the Second International Clean Air Congress. H. M. Englund and W. T. Berry (eds.). p. 249-255. Academic Press, New York.

Hill, G. R. Jr. and M. D. Thomas. 1933 Influence of leaf destruction by sulphur dioxide and by clipping on the yield of alfalfa. Plant Physiol. 8:223-245.

Jones, F. G. W., R. A. Dunning and K. P. Humphries. 1955 The effects of defoliation and loss of stand upon yield of sugar beet. Ann. Appl. Biol. 43:63-70.

Kendall, M. G. 1957 A course in multivariate analysis. Hafner, New York.

Lacasse, N. L. and W. J. Moroz. 1969 Handbook of effects assessment: Vegetation damage. Center for Air Environment Studies, The Pennsylvania State Univ., Univ. Park, Penn.

Lewin, J. and J. Lomas. 1974 A comparison of statistical and soil moisture modeling techniques in a long-term study of wheat yield performance under semi-arid conditions. J. Appl. Ecol. 11:1081-1090.

Liu, B. and E. S. Yu. 1976 Damage functions for air pollutants. Midwest Research Institute. EPA Contract No. 68-01-2968. Kansas City, Mo.

Lomas, J. 1972 Economic significance of dry-land farming in the arid northern Negev of Israel. Agric. Meteorol. 10:383-392.

Lomas, J. and Y. Shashoua. 1973 The effect of rainfall on wheat yields in an arid region. In: Plant response to climatic factors. R. O. Slatyer, (ed.) p. 531-538. Unesco, Paris.

Middleton, J. T. and A. O. Paulus. 1956 The identification and distribution of air pollutants through plant response. Arch. Indust. Health. 14:526-532.

Millican, A. A. 1976 A survey and assessment of air pollution damage to California vegetation, 1970 through 1974. State of California, Dept. of Food and Agriculture.

Millican, A. A. 1971 A survey and assessment of air pollution damage to California. State Dept. of Agriculture, Sacramento, Ca.

Naegele, J. A., W. A. Feder and C. J. Brandt. 1972 Assessment of air pollution damage to vegetation in New England July 1971- July 1972. Final Repart. Waltham Mass., Suburban Expt. Sta.

Oshima, R. J. 1975 Development of a system for evaluating and reproting economic crop losses caused by air pollution in California. III. Ozone dosage-crop loss conversion function alfalfa, sweet corn; Final Report to the State of California, Air Resources Board under Agreement ARB 3-690.

Oshima, R. J. 1974 Development of a system for evaluating and reporting economic crop losses caused by air pollution in California. II. Yield study; Final Report to the State of California, Air Resources Board under Agreement ARB 2-704.

Oshima, R. J., M. P. Doe, P. K. Braegelman, D. W. Baldwin and V. Van Way. 1976 Ozone dosage-crop loss function for alfalfa: A standardized method for assessing crop losses from air pollutants. Air Pollu. Cont. Assoc. J. 26:861-865.

Pell, E. J. and E. Brennan. 1975 Economic impact of air pollution on vegetation in New Jersey and an interpretation of its annual variability. Environ. Pollu. 8:23-33.

Penman, H. L. 1962 Woburn irrigation, 1951-1959. II. Results for grass. J. Agric. Sci. 58:349-364.

Phipps, R. H., R. J. Fulford and F. C. Crofts. 1975 Relationships between the production of forage maize and accumulated temperature, Ontario heat units and solar radiation. Agric. Meteorol. 14:385-397.

Richard, L. C. and L. O. Pochop. 1975 Principal components and crop weather analysis. Trans. Amer. Soc. Agric. Eng. 18:335-339.

Robertson, G. W. 1975 Rice and weather. Technical Note No. 144. WMO Pub. No. 423. p.40.

Robertson, G. W. 1974 Wheat yields for 50 years at Swift Current, Saskatchewan, in relation to weather. Can. J. Plant Sci. 54:625-650.

Shawcroft, R. W., E. R. Lemon, L. H. Allen, Jr., D. W. Stewart and S. E. Jensen. 1974 The soil-plant-atmosphere model and some of its predictions. Agric. Meteorol. 14:286-307.

Smith, L. P. 1960 The relation between weather and meadow hay yields in England, 1939-1956. J. Brit. Grassld. Soc. 15(3):203-208.

Splinter, W. E. 1974 Modelling of plant growth for yield prediction. Agric. Meteorol. 14:243-253.

Stanhill, G. 1973 Simplified agroclimatic procedures for assessing the effect of water supply. In: Plant response to climatic factors. R. O. Slatyer (ed.) p. 461-476. Unesco, Paris.

Staple, W. J. and J. J. Lehane. 1954a Wheat yield and use of moisture on substations in southern Sasketchewan. Can. J. Agric. Sci. 34:460-468.

Staple, W. J. and J. J. Lehane. 1954b Weather conditions influencing wheat yields in tanks and field plots. Can. J. Agric. Sci. 34:553-564.

Stewart, J. I., R. D. Misra, W. O. Pruitt and R. M. Hagan. 1975 Irrigating corn and grain sorghum with a deficient water supply. Amer. Soc. Agric. Eng. 18:270-280.

Thompson, L. M. 1964 Our recent high yields - How much due to weather? In: Research on water. A symposium. p. 74-84. Amer. Soc. Agron. Spec. Pub. No. 4, Madison, Wisc.

Thompson, L. M. 1963 Weather and technology in the production of corn and soybeans. CAED Report 17. Center for Agric. and Econ. Devel. Ames, Iowa.

Thompson, L. M. 1962 Evaluation of weather factors in the production of wheat. J. Soil. Water Conserv. 17:149-156.

Thompson, C. R. and O. C. Taylor. 1969 Effects of air pollutants on growth, leaf drop, fruit drop, and yield of citrus trees. Environ. Sci. Tech. 3:934-940.

Waddell, T. E. 1974 The economic damages of air pollution. Washington Environmental Research Center, U.S. E.P.A., Washington, D. C.

Weidensaul, T. C. and N. L. Lacasse. 1972 Results of the 1969 statewide survey of air pollution damage to vegetation in Pennsylvania. Pl. Dis. Reptr. 56:701-704.

Westman, W. E. and W. D. Conn. 1976 Quantifying benefits of pollution control: Benefits of controlling air and water pollution from energy production and use. Report to Energy Resources Conserv. and Devel. Comm., State of California.

Williams, G. D. V. 1969 Weather and prairie wheat production. Can. J. Agric. Econ. 17(1):99-109.

Winkler, R. L. 1967 The assessment of prior distributions in Bayesian analysis. J. Amer. Statistical Assoc. 62:776-800.

Zellner, A. 1971 An introduction to Bayesian inference in econometrics. John Wiley.

Zellner, A. and J. F. Richard. 1973 Use of prior information in the analysis and estimation of Cobb-Douglas proudction function models. International Econ. Rev. 14(1):107-119.

REFERENCES - SECTION VI-A

Baumol, W. J. 1965 Economic theory and operations analysis. Prentice-Hall, Inc. Englewood Cliffs, New Jersey.

Boehlje, M. 1967 An analysis of the impact of selected factors in the process of farm firm growth. Unpublished M.S. thesis, Purdue University.

Boussard, J. M. 1971 A model of the behavior of farmers and its application to agricultural policies. European Econ. Rev. 2:436-461.

Boussard, J. M. and M. Petit. 1967 Representation of farmers' behavior under uncertainty with a focus-loss constraint. J. Farm Econ. 49(4): 869-880.

Cocks, K. D. 1968 Discrete stochastic programming. Management Sci. 15(1):72-79.

Day, R. H. 1963a On aggregating linear programming models of production. J. of Farm Econ. 45(4):797-813.

Day, R. H. 1963b Recursive programming and production response. North Holland Publishing Co., Amsterdam.

Dean, G. W. and H. O. Carter. 1961 Guides to profitable cropping systems for Yolo County farms. Geannini Found. Res. Rept. No. 242.

Freund, R. J. 1956 The introduction of risk into a programming model. Econometrica 24:253-264.

Gilson, J. C. 1960 Economic aspects of alternative crop rotations and beef production systems. Faculty of Agric. and Home Econ. University of Manitoba, Winnipeg, Technical Bull. No. 3.

Hazell, P. B. R. 1971 A linear alternative to quadratic and semivariance programming for farm planning under uncertainty. Amer. J. Agric. Econ. 53(1):53-62.

Hazell, P. B. R. 1970 Game theory - An extension of its application to farm planning under uncertainty. J. Agric. Econ. 21:239-252.

Heady, E. O. and W. Candler. 1964 Linear programming methods. Iowa State Univ. Press, Ames, Iowa.

Horner, G. L. 1975 Internalizing agricultural nitrogen pollution externalities: A case study. Amer. J. Agric. Econ. 57(1):33-39.

How, R. B. and P. B. R. Hazell. 1968 Use of quadratic programming in farm planning under uncertainty. Dept. of Agric. Econ., A. E. Res. 250, Cornell University.

Johnson, S. R., K. R. Terfertiller and D. S. Moore. 1967 Stochastic LP and feasibility problems in farm growth analysis. J. Farm Econ. 49: 908-919.

King, G. A. 1975 Econometric models of the agricultural sector. Amer. J. Agric. Econ. 57:164-171.

Kennedy, J. O. S. and E. M. Francisco. 1974 On the formulation of risk constraints in linear programming. J. Agric. Econ. 25(2):129-142.

Kohn, R. E. 1971 Application of linear programming to a controversy on air pollution control. Management Sci. 17(10):B-609 - B-621.

Lee, J. E. 1966 Exact aggregation - A discussion of Miller's theorem. Agric. Econ. Res. p. 58-61.

Lin, W.,G. W. Dean and C. V. Moore. 1974 An empirical test of utility vs. profit maximization in agricultural production. Amer. J. Agric. Econ. 56(3):497-508.

Miller, T. 1966 Sufficient conditions for exact aggregation in linear programming models. Agric. Econ. Res. p. 52-57.

Nerlove, M. and K. L. Bachman. 1960 The analysis of changes in agricultural supply : Problems and approaches. J. Farm Econ. 42:531-554.

Paris, Q. and G. C. Rausser. 1973 Linear programming and the aggregation problem. Unpublished paper, Dept. Agric. Econ., U. C. Davis.

Rae, A. N. 1971 An empirical application and evaluation of discrete stochastic programming in farm management. Amer. J. Agric. Econ. 53(4): 625-638.

Sahi, R. K. and W. J. Craddock. 1974 Estimation of flexibility coefficients for recursive programming models - Alternative approaches. Amer. J. Agric. Econ. 56(2):344-350.

Schaller and G. W. Dean. 1965 Predicting regional crop production. U.S. Dept. Agric. Tech. Bull. 1329.

Stovall, J. G. 1966 Income variation and selection of enterprises. J. Farm Econ. 48:1575-1579.

Webster, J. P. G. and J. O. S. Kennedy. 1975 Measuring farmers' tradeoffs between expected income and focus-loss income. Amer. J. Agric. Econ. 57(1):97-105.

Wiens, T. B. 1976 Peasant risk aversion and allocative behavior: A quadratic programming approach. Amer. J. Agric. Econ. 58(4):629-635.

REFERENCES - SECTION VI-B

Armstrong, D. L., L. J. Conner and R. P. Strickland. 1970 Combining simulation and linear programming in studying farm firm growth. Simulation uses in agricultural economics. Michigan State Univ., Agric. Econ. Rept. No. 157.

Chien, Y. I. and G. L. Bradford. 1976 A sequential model of the farm firm growth process. Amer. J. Agric. Econ. 58(3):456-465.

Chou, T. H. and E. O. Heady. 1961 Applications in integer programming. Can. J. Agric. Econ. 9:54-67.

Eidman, V. R., G. W. Dean and H. O. Carter. 1967 An application of statistical decision theory to commercial turkey production. J. Farm Econ. 852-868.

Glickstein, A., E. M. Bobb, C. E. French and J. H. Greene. 1962 Simulation procedures for production control in an Indiana cheese plant. Purdue Agric. Expt. Sta. Res. Bull. No. 757.

Halter, A. N. and G. W. Dean. 1965 Use of simulation in evaluating management policies under uncertainty: An application to a large scale ranch. J. Farm Econ. 47(3):557-573.

Horner, G. and M. English. 1976 Can water pricing solve the water quality problem? Paper presented to Western Agric. Econ. Assoc. Meeting.

Johnson, S. R. and G. C. Rausser. 1972 A survey of systems analysis and simulation in agricultural economics. Dept. Agric. Econ., Univ. of California, Davis.

La Due, E. L. and W. H. Vincent. 1974 Systems theory and simulation: A critique of the literature. Agric. Econ. Rept. No. 261, Dept. of Agric. Econ., Michigan State Univ.

Naylor, T. H., J. L. Balintfy, D. S. Burdick and K. Chu. 1968 Computer simulation techniques. Wiley and Sons, Inc. New York.

Nerlove, M. 1958 The dynamics of supply: Estimation of farmer's response to price. Johns Hopkins Press, Baltimore.

Orcutt, G. H. 1960 Simulation of economic systems. Amer. Econ. Rev. 50(5):893-907.

Patrick, G. F. and L. M. Eisgruber. 1968 The impact of managerial ability and capital structure on growth of the farm firm. Amer. J. Agric. Econ. 50:491-506.

Shechter, M. and E. O. Heady. 1970 Response surface analysis and simulation models in policy choices. Amer. J. Agric. Econ. 52(1):41-50.

REFERENCES - SECTION VI-C

Arrow, K. J., H. B. Chenery, B. S. Minhas and R. M. Solow. 1961 Capital labor substitution and economic efficiency. Rev. Econ. Statistics 43: 225-250.

Doll, J. P. 1974 On exact multicollinearity and the estimation of the Cobb-Douglas production function. Amer. J. Agric. Econ. 56(3):556-563.

Foote, R. J. 1955 A comparison of single and simultaneous equation tehcniques. J. Farm Econ. 37(5):975-990.

Goldberger, A. 1964 Econometric theory. Wiley and Sons, New York.

Griliches, Z. 1963 Estimates of the aggregate agricultural production function from cross-sectional data. J. Farm Econ. 45(2):419-428.

Griliches, Z. 1964 Research expenditures, education, and the aggregate agricultural production function. Amer. Econ. Rev. LIV(6).

Griliches, Z. 1957 Specification bias in estimation of production functions. J. Farm Econ. 39(1):8-20.

Heady, E. O. and J. L. Dillon. 1961 Agricultural production functions. Ames, Iowa: Iowa State University Press.

Hoch, I. 1962 Estimation of production function parameters combining time series and cross-section data. Econometrica 30(1):34-53.

Hoch, I. 1976a Production functions and supply applications for California dairy farms. Giannini Foundation Monograph No. 36, Univ. of Calif., Berkeley.

Hoch, I. 1976b Returns to scale in farming: further evidence. Amer. J. Agric. Econ. 58(4):745-749.

Hoch, I. 1958 Simultaneous equation bias in the context of the Cobb-Douglas production function. Econometrica 26(4).

De Janvry, A. 1972 Optimal levels of fertilization under risk: The potential for corn and wheat fertilization. Amer. J. Agric. Econ. 54(1): 1-10.

Just, R. E. 1974 An investigation of the importance of risk in farmers' decisions. Amer. J. Agric. Econ. 56(1):14-25.

Lau, L. J. and P. A. Yotopoulos. 1972 Profit, supply and factor demand functions. Amer. J. Agric. Econ. 54(1):11-18.

Malinvaud, E. 1966 Statistical methods of econometrics. Rand McNally and Co., Chicago; North-Holland Publishing Co., Amsterdam.

Paris, Q. and I. Hoch. 1966 Cobminations of time series and cross sectional data in dairy production function analysis. Proceedings, Western Farm Economics Assoc. p. 247-258.

Sarhan, M., R. E. Howitt and C. V. Moore. 1976 An economic analysis of Mosquito control. Unpublished paper, Dept. of Agric. Econ., Univ. of Calif., Davis.

Solow, R. M. 1957 Technical change and the aggregate production function. Rev. Econ. Statistics 39:312-320.

Theil, H. 1971 Principles of econometrics. Wiley and Sons, New York.

Ulveling, E. F. and L. B. Fletcher. 1970 A Cobb-Douglas function with variable returns to scale. Amer. J. Agric. Econ. 52(2):322-326.

Vandenborre, R. J. 1968 Dynamic impact multipliers: a case study of white dry edible beans. Amer. J. Agric. Econ. 50(2):311-327.

Zellner, A. 1962 An efficient method of estimating seemingly unrelated regressions and tests for aggregation bias. J. Amer. Statistical Assoc. 57(298):348-368.

REFERENCES - SECTION VII-A

Ayres, R. and A. Kneese. 1970 Production, consumption, and externalities. Amer. Econ. Rev. 59:3-14.

Dean, G. W., H. V. Carter, E. A. Nickerson and R. M. Adams. 1973 Structure and projections of the Humboldt County economy: Economic growth versus environmental quality. Calif. Agric. Expt. Sta., Giannini Fundation Res. Rpt. No. 318.

Gass, S. 1969 Linear programming. 3rd ed. McGraw-Hill, New York.

Isard, W. 1960 Methods of regional analysis: An introduction to regional science. M.I.T.: The technology press and Wiley and Sons, Inc. New York.

Laurent, E. A. and J. C. Hite. 1971 Economic-ecologic analysis in the Charleston metropolitan area. Clemson, South Carolina: Water Resources Res. Inst., Clemson Univ.

Leontief, W. 1966 Input-output economics. Oxford Univ. Press.

Leontief, W. W. 1951 The structure of the American economy, 1919-1939. 2nd ed. Oxford Univ. Press, New York.

Miernyk, W. H. 1965 The elements of input-output analysis. Random House, New York.

Simpson, J. P. and J. W. Adams. 1975 Disaggregation of input-output models into product lines as an economic development policy tool. Amer. J. Agric. Econ. 57(4):584-590.

Wagner, H. M. 1954 A linear programming solution to dynamic Leontief type models. RAND report RM-1343, The Rand Corporation, Santa Monica, California.

REFERENCES - SECTION VII-B

Adams, R. M. 1975 A quadratic programming approach to the production of California field and vegetable crops emphasizing land, water and energy use. Unpublished Ph.D. dissertation, Univ. of Calif., Davis.

Bawden, D. L. 1964 An evaluation of alternative spatial models. J. Farm Econ. 46(5):1372-1379.

Beckmann, M. and T. Marschak. 1955 An activity analysis approach to location theory. In: Proceedings of the second symposium in linear programming, Washington, D.C. p. 331-379.

Duloy, J. H. and R. D. Norton. 1973 CHAC, A programming model of Maxican agriculture. In: Multi-level planning: Case studies in Mexico. L. Goreux and A. Manne, eds. North Holland Publishing Co. Amsterdam.

Egbert, A. C. and E. O. Heady. 1961 Regional adjustments in grain production: A linear programming analysis. U.S.D.A. Tech. Bull. 1241.

Hall, H. H., E. O. Heady and Y. Plessner. 1968 Quadratic programming solution of competitive equilibrium for U.S. Agriculture. Amer. J. Agric. Econ. 50(3):536-555.

Hazell, P. B. R. and P. L. Scandizzo. 1974 Competitive demand structures under risk in agricultural linear programming models. Amer. J. Agric. Econ. 56(2):235-244.

Hazell, P. B. R. and P. L. Scandizzo. 1973 Competitive demand structures under risk in agricultural linear programming models. Contributed paper, Amer. Agric. Econ. Assoc. meeting, Edmonton, Canada.

Heady, E. O. and H. H. Hall. 1968 Linear and nonlinear spatial models in agricultural competition, land use and production potential. Amer. J. Agric. Econ. 50(5):1539-1548.

Heady, E. O. and N. K. Whittlesey. 1965 A programming analysis of interregional competition and surplus capacity in American agriculture. Iowa Agric. and Home Econ. Dept. Expt. Sta. Res. Bull. 538.

Samuelson, P. A. 1952 Spatial price equilibrium and linear programming. Amer. Econ. Rev. 42:283-303.

Takayama, T. and G. G. Judge. 1964 An interregional activity analysis model for the agricultural sector. J. Farm Econ. 46(2):349-365.

REFERENCES - SECTION VIII

Akino, M. and Y. Hayami. 1975 Efficiency and equity in public research: Rice breeding in Japan's economic development. Amer. J. Agric. Econ. 57(1):1-10.

Bieri, J. and A. Schmitz. 1974 Market intermediaries and price instability: Some welfare implications. Amer. J. Agric. Econ. 56(2):280-285.

Ferguson, C. E. 1969 Microeconomic theory, (1969, Revised ed.) Homewood, Ill.; R. D. Irwin.

George, P. S. and G. A. King. 1971 Consumer demand for food commodities in the United States with projections for 1980. Calif. Agric. Expt. Sta. Giannini Foundation Monograph No. 26.

Hazell, P. B. R. and P. L. Scandizzo. 1975 Market intervention policies when production is risky. Amer. J. Agric. Econ. 57(4):641-649.

Henderson, J. and R. Quandt. 1971 Microeconomic theory. (2nd ed). McGraw Hill Co., New York.

Massell, B. F. 1969 Price stabilization and welfare. Quart. J. Econ. 83(2):284-298.

Newbery, D. 1976 Feasible price stability may not be desirable. Inst. Math. studies in the Social Sci., Stanford Univ. Working Paper No. 68.

Oi, W. 1961 The desirability of price instability under perfect competition. Econometrica 29:58-64.

Samuelson, P. A. 1972 The consumer does benefit from feasible price instability. Quart. J. Econ. 86:476-493.

Subotnik, A. and J. Houck. 1976 Welfare implications of stabilizing consumption and production. Amer. J. Agric. Econ. 58(1):13-20.

Turnovsky, S. J. 1974 Price expectations and the welfare gains from price stabilization. Amer. J. Agric. Econ. 56(4):706-716.

Waugh, F. 1944 Does the consumer benefit from price instability? Quart. J. Econ. 58:602-614.

Wold, H. 1953 Demand analysis. John Wiley and Sons, Inc., New York.